SST

AN ECONOMIC ANALYSIS

Part III. Contractor's Reports

C. Sonic Boom

UNITED STATES DEPARTMENT OF COMMERCE

EXPLANATION OF RELEVANCY OF CONCLUSIONS AND DATA CONTAINED IN THE SST ECONOMIC ANALYSIS REPORTS PREPARED BY THE DEPARTMENT OF COMMERCE

In an effort to provide as complete a history as possible of the course of the SST program, materials consisting of Part I, Executive Summary and Supplements, and Part III, Contractor's Reports*, have been made publicly available. However, all persons using these materials should be advised that the data and conclusions pertaining to the SST designs contained therein are not current and have been superseded by the SST designs submitted to the FAA September 6, 1966, which were the basis for the Economic Feasibility Report prepared by the FAA in April 1967 and for the reports of the Economic Research Contractors submitted December 31, 1966. Using the superseded designs and the related economic data for comparisons with economic characteristics of other aircraft, both American and European, could be misleading and not representative of what was achieved with the more recent SST designs.

Because of the changes in development costs and total program costs and because of the provisions of the Phase III contracts with the airframe and engine manufacturers, the financial data and conclusions contained in the Executive Summary relating to the financial capability of the manufacturers do not reflect their financial capability in the context of the current program or their general financial position.

Accordingly, the materials attached hereto should be viewed as predominately historical in character.

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* Part II of the SST Economic Analysis was never issued.

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IDA Special Report

ECONOMIC EFFECTS OF SST SONIC BOOM

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INTRODUCTION

1.1 BACKGROUND OF THE STUDY

This study was performed for the Supersonic Transport Study Group under US Department of Commerce Contract No. C-30-65 (Neg), dated October 29, 1964, which called for "services to conduct a study on the Economic Effects of Sonic Boom created by Supersonic Transport Operations. . . ." Principal authors of the study were Mr. Norman J. Asher (project leader), Dr. Stanley W. Dziuban, and Dr. William Hamburger.

1.2 PURPOSE

The purpose of this study is to estimate claims costs resulting from the sonic boom of the SST, and to examine tradeoffs between these costs and aircraft operating costs for various operating procedures designed to reduce claims costs. The study does not evaluate any of the psychological or emotional reactions to the SST boom, nor does it deal with potential social-political problems that could result from such reactions.

1.3 METHOD OF ANALYSIS

Data on claims resulting from supersonic operation of military airplanes in the US were reviewed. Since the great majority of claims are for damage to ground structures, a study was made of structural responses to sonic booms as an aid in interpreting claims data and in extrapolating claims costs from smaller aircraft to the SST. A relationship between claims cost and population exposure to sonic boom was developed for the US. This relationship was then used to project tradeoffs between claims costs and the cost of modifying SST operations in the US so as to reduce claims.

Claims costs resulting from SST operations over foreign routes will probably be quite different from those of comparable US routes because of differing types of ground structures. Therefore, foreign routes were categorized only qualitatively according to the number of people boomed, the ease of avoiding population, and the susceptibility of ground structures to damage.

1.4 VALIDITY OF THE ANALYSIS

The two basic sources of claims data studied were claims resulting from normal US Air Force supersonic operations in the US and from the Oklahoma City test claims. We have concluded that the Oklahoma City data are more representative of future SST operations since the experiment was specifically designed to simulate the SST sonic

boom environment. At this writing (November 1964), claims resulting from the Oklahoma City tests were still being received by the Judge Advocate's Office at Tinker Field at a rate of 100 per week. Further, litigation involving past claims is a possibility. Accordingly, the present pattern of claims costs at Oklahoma City could be changed by the time the books are closed on that experiment. Our judgment, however, is that the Oklahoma City pattern will not be drastically altered by claims not yet submitted or evaluated or by future litigation of claims.

Since the filing of claims involves emotional as well as purely physical factors, the claims resulting from commercial SST operations over a long period of years involving night as well as daytime operations could be very different from the Oklahoma City pattern. Notwithstanding this possibility, we have no basis for either increasing or decreasing the Oklahoma City level of claims in predicting future SST claims and feel that as of this date the Oklahoma City data provide the best means available for projecting the general level and pattern of SST claims.

2

MAJOR CONCLUSIONS

2

MAJOR CONCLUSIONS

2.1 CLAIMS COSTS

Claims for damage to ground structures comprise by far the largest category of claims. Based on the Oklahoma City data, the major item of cost was administrative handling of the claims. Actual payments for alleged damages were small. The claims costs are directly proportional to the number and value of the buildings overflown, which are approximated in this study by the population overflown. The Oklahoma City claims data are representative of the situation that may exist in the US and Canada during the SST operations. However, they are almost certainly not representative of the situation that will be found in other areas of the world, particularly in the areas with very different climatic conditions or level of economic development.

Up to a point, ground damage claims costs can be reduced by circuitous routing and extended subsonic operation at relatively small increases in operating costs. For example, our optimal route modification would reduce annual claims costs by about 45 percent (from about $104,000,000 to $58,000,000) but would increase operating costs by only about 1 percent (from $1,314,000,000 to $1,328,000,000). However, the cost of further operating restrictions tends to increase faster than the savings realized by claims reduction.

2.2 STRUCTURAL RESPONSE

SST operations should not damage the basic structure of reasonably well-constructed buildings. Occasional damage to residences will, therefore, be minor and involve only bric-a-brac and secondary structural elements such as plaster, interior surfaces, and glass. Damage to commercial, industrial, and other nonresidential buildings should be limited to only occasional glass breakage.

2.3 LIABILITY FOR SONIC BOOM GROUND DAMAGE

The estimates of SST ground damage claims costs are based almost entirely on the data collected by the FAA during the experiments conducted at Oklahoma City, where the Federal government assumed liability. However, it is not clear that an airline (or the Federal government, for that matter) would be liable for sonic boom damage resulting from the operation of a commercial transport, flown in accordance with flight rules and procedures prescribed by the federal government. The final determination as to who is liable and for what effects could significantly affect the level of claims costs resulting from SST sonic booms

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CLAIMS DATA

3.1 INTRODUCTION AND CONCLUSIONS

In this section we consider the damage claims record of the Oklahoma City experiment and compare it with some previous experience. As the analytical framework for the interpretation of these data, a theoretical damage model is developed in Section 3.2; the social factors that limit the validity of this model are discussed in Section 3.3. The claims data examined in Section 3.4 are too limited to permit any strong conclusions. They do, however, give some support to the hypotheses that ground damage costs incurred in SST operations will, for given overpressures, be independent of boom impulse. Our model suggests that they will vary only moderately with the frequency of flights conducted over a given track. The data also provide a measure of the "equilibrium" rate of damage claims that may be expected after the higher claims rate experienced initially.

3.2 MODELS OF TRUE SONIC BOOM DAMAGE

3.2.1. Basic Features of the Model

The most important feature of our boom-damage model is that it recognizes that sonic booms do not generally break items of ordinary quality but mainly contribute to the breakage of items that have been made vulnerable by other causes* (see Section 3.4.3. and Section 5). Thus, there will always be some breakage associated with sonic booms because vulnerable items will continuously be generated by other factors at a rate that is "proportional to the number of people or houses in the area and independent of the intensity and frequency of booms." Therefore, in considering a fixed geographical area, we assume that breakable items of varying susceptibility enter the boomed population at a fixed rate.

It would seem that, with vulnerable items entering the population at a fixed rate, all items would eventually become vulnerable to breakage. Our model avoids this implication by recognizing that items vulnerable to sonic boom breakage are also vulnerable to breakage from other causes, such as wind pressures, passing trucks, slamming doors,

*Were this not the case, we would expect sonic boom damage to be a one-time thing (on any particular route), since property owners would, presumably, replace the item broken with something sufficiently strong or new that it would not have the initial vulnerability.

or an intensification of the causes that made the items vulnerable in the first place (e.g., shifting foundations). Hence breakable items are continually passing out of the population even in the absence of sonic boom.

These opposing tendencies (the flow of breakable items into and out of the population—including those removed by booms) lead to a statistically stationary population of breakable items.

Another feature of the model is that it is intrinsically stochastic. The first boom of a given type (e.g., that produced by an aircraft of given speed, weight, and altitude) does not break all existing items vulnerable to that type of boom, largely because a given "type" of boom can give rise to any of a broad range of actual forces (depending on atmospheric factors) and perhaps also because an item's vulnerability to breakage may vary from moment to moment. Hence we represent the effect of a given type of boom upon a given class of breakable items as a breakage rate or percentage, corresponding to a breakage probability for an individual item of that class.

Under these assumptions, the population of breakable items in an area depends, in part, on the previous history of booms in that area. An area that has not been previously boomed would obviously have a greater inventory of breakable items and would therefore sustain a higher initial breakage rate than that same area will experience at a subsequent date, when the population of breakable items has been reduced by booms. To explore the quantitative meaning of this theory, we must formulate a suitable notation and some assumptions. Those described in the following section are especially simple to work with.

3.2.2. Definitions and General Assumptions

The following definitions will be used in developing a boom-damage model:

x = the strength of an item. An item with low strength is particularly susceptible to breakage. x may be defined, more specifically, as that boom intensity (y) which has a 50-50 chance of breaking the item.

$A(x)$ = the rate (per day) at which items with a strength of x enter the population of breakable items.

$B(x)$ = the rate (per day and per item) at which items with a strength of x are eliminated from the population by causes other than sonic booms. (We shall assume that these other causes are other forms of damage.)

$C(x, y)$ = the rate (per boom and per item) at which items with a strength of x are eliminated from the population by sonic booms of intensity y. Note that by taking $C(x, y)$ to be independent of the history of previous booms we are precluding "fatigue" effects.

r = the frequency of booms (per day).

$rC(x,y)$ = the rate (per day and per item) of boom-caused damage. (We implicitly assume that r and $C(x,y)$ are small.)

$D_{y_1 y_2}(x)$ = the observed per-day rate at which items with strength x are damaged by booms of intensity y_2 hitting a population with previous exposure to booms of intensity y_1. For instance, D_{0y} represents the initial rate of damage caused by booms of intensity y. To keep the notation simple, the subscripts to D refer explicitly only to boom intensities. The actual damage rates would, of course, depend also on the associated boom (or flight) frequencies.

$\overline{D}_{y_1 y_2}$ = the observed rate of damage to <u>all</u> items under the condition set forth in the preceding paragraph.

$N_y(x)$ = the number of items with strength x existing after equilibrium is reached with booms of intensity y.

$f(y)$ and $g(y)$ are defined in the text accompanying equations (9) and (15) below.

3.2.3. Implications of the General Model

We solve first for $N_0(x)$, the population of breakable items existing before booms start. Since this population is replenished at rate $A(x)$ and depleted at rate $N_0(x) \cdot B(x)$, equilibrium is reached when the two rates are equal:

$$N_0(x) \cdot B(x) = A(x) \tag{1}$$

$$N_0(x) = \frac{A(x)}{B(x)} \tag{2}$$

Similarly, we may solve for $N_y(x)$, considering that we now have breakage also from sonic booms of magnitude y at a rate of $N_y(x) \cdot rC(x,y)$.

$$N_y(x)\left[B(x) + rC(x,y)\right] = A(x) \tag{3}$$

$$N_y(x) = \frac{A(x)}{B(x) + rC(x,y)} \tag{4}$$

The corresponding rates of damage are:

$$D_{0y}(x) = rC(x,y) \cdot N_0(x) = \frac{rC(x,y) \cdot A(x)}{B(x)} \tag{5}$$

and

$$D_{yy}(x) = rC(x,y) \cdot N_y(x) = \frac{rC(x,y) \cdot A(x)}{B(x) + rC(x,y)} \tag{6}$$

Extending this reasoning to the case of booms of magnitude y_2 hitting an area that has previously reached equilibrium under magnitude y_1 booms, we have:

$$D_{y_1 y_2}(x) = r_2 C(x,y_2) \cdot N_{y_1}(x) = \frac{r_2 C(x,y_2) \cdot A(x)}{B(x) + r_1 C(x,y_1)}\,. \tag{7}$$

The total damage to all items is the integral of the above:

$$\bar{D}_{y_1 y_2} = \int_{x=0}^{\max.\ x} \frac{r_2 C(x, y_2) \cdot A(x)}{B(x) + r_1 C(x, y_1)} \, dx \quad . \tag{8}$$

(We have indicated "max. x" as the upper limit of this integral, to allow for later introduction of an upper limit on x .) Without such a limit on x , the integral extends from zero to infinity.)

3.2.4. <u>The "Mimicry" Assumption (Model I) and Its Implications</u>

We do not, at this point, know the forms of the functions A , B , and C , so we shall merely try out some simple and more or less plausible assumptions regarding them to see where they lead us.

Let us assume, for instance, that the functions B(x) and C(x) are proportional, (i.e., that boom damage "mimics" ordinary damage) so that for any given boom magnitude the fraction of items removed from the population of breakable items is the same as the fraction broken by the boom, regardless of the strength of the item. We therefore have

$$rC(x,y) = rf(y) \cdot B(x) \tag{9}$$

where $rf(y)$ is the frequency of boom damage caused by r daily booms of intensity y , relative to the rate, B(x) , at which items break through other causes. In that case,

$$\bar{D}_{y_1 y_2} = \frac{\displaystyle\int \frac{r_2 f(y_2) B(x) A(x)}{B(x) + r_1 f(y_1) B(x)} \, dx}{\displaystyle\int A(x) \, dx} = \frac{r_2 f(y_2)}{1 + r_1 f(y_1)} \, , \tag{10}$$

$$\bar{D}_{yy} = \frac{\displaystyle\int \frac{rf(y) B(x) A(x)}{B(x) + rf(y) B(x)} \, dx}{\displaystyle\int A(x) \, dx} = \frac{f(r,y)}{1 + f(r,y)} \, , \tag{11}$$

$$\frac{\bar{D}_{y_1 y_2}}{\bar{D}_{y_2 y_2}} = \frac{1 + r_2 f(y_2)}{1 + r_1 f(y_1)} \, , \tag{12}$$

and similarly for other damage rates and ratios, such as

$$\frac{\bar{D}_{y_2 y_2}}{\bar{D}_{y_1 y_1}} = \frac{r_2 f(y_2)}{r_1 f(y_1)} \cdot \frac{1 + r_1 f(y_1)}{1 + r_2 f(y_2)} \, . \tag{13}$$

For small values of rf (i.e., a situation in which sonic boom causes relatively little damage compared with the rate, B) the "impact ratio," (Eq. 12), is less than $r_2 f(y_2) \big/ r_1 f(y_1)$, but it approaches that ratio for large values of $rf(y)$. The equilibrium damage ratio, (Eq. 13), approaches the corresponding rf ratio for very small values of f , but approaches 1 for large values of rf .

[redacted]

To get some estimate of the magnitude of rf in the Oklahoma City experiment, we may consider approximate values of 7.2 for r and 7 for the ratio

$$\frac{D_{0y}}{D_{yy}} = 1 + rf(y) \tag{14}$$

leading to a value of 6 for $rf(y)$ and 0.83 for $f(y)$. With such a large value for rf, we would "conclude" that impact ratios faithfully reflect rf ratios and that steady-state damage is almost independent of boom intensities and steady-state frequencies. (Short-period fluctuations in boom intensity or frequency would, of course, produce corresponding variations in damage rates per day.)

3.2.5. The "Selectivity" Assumption (Model II) and Its Implications

We have assumed, so far, that booms increase the rate of breakage over the natural rate of removal, B, for all items equally. Strong booms differ from weak booms, under that assumption, only in causing more breakage of all existing items.

We shall now explore a different view, namely, that booms are highly selective in damaging exposed items. The simplest version of this view is that a boom of strength y will never break any items of much greater strength. (It is interesting to note that, in Air Force damage claims adjudication, it is often assumed that booms cannot break items with strengths greater than $3y$.)

We shall explore this consideration by placing an upper limit of ky on the integral $\int A(x)\, dx$ and introducing the notation

$$g(y) = \int_{x=0}^{ky} A(x)\, dx \,. \tag{15}$$

Our damage rate formulas now contain the factor $g(y)$, representing the maximum rate of steady-state boom damage, whereas in the previous model all damage rates had the common constant,

$$\int_{x=0}^{\infty} A(x)\, dx \,.$$

As a result, the damage rates may now show any sort of effect of y, depending on the form of the function $g(y)$ or of the function $A(x)$ from which it is derived. For instance, if $A(x)$ is a constant, $g(y)$ will be proportional to y; if $A(x)$ is proportional to x, then $g(y)$ will vary with the square of y, and so forth. The conclusions of the previous model still hold, though, insofar as they pertain to the effect of boom frequency or to the general features of the distinction between steady-state and impact damage rates.

3.2.6. Conclusions

The foregoing models make a strong distinction between initial or "impact" damage rates, on the one hand, and steady-state damage rates, on the other. They provide ratios between damage rates under various circumstances. Model I is narrowly restricted to circumstances under which sonic boom damage rates "mimic" the natural removal rates, B ; it entails strong implications regarding the effects of both frequency and intensity of booms. Model II drastically modifies this "mimicry" assumption by supposing that sonic boom damage is limited to a group of items whose strength is sufficiently low. This frees it of the implications of Model I regarding the effects of different boom intensities while retaining the other features of Model I.

3.3 SOCIAL ASPECTS OF SONIC BOOM DAMAGE CLAIMS

It was apparently the view of FAA claims investigators that the sonic booms caused no damage in Oklahoma City, or at least none that would not promptly have occurred anyhow. After an initial period of learning what to look for and how to interpret what they saw, during which they did recommend approval of a number of claims, the investigators found virtually none (so far as we know, they found four since early May) which, according to them, warranted approval. Nevertheless, claims continued to be filed by the public and some continued to be approved by the Air Force legal officers responsible for this decision. The filing and paying of claims must therefore be viewed as a phenomenon that goes beyond the simple world of true sonic boom damage and involves elements of personal judgment and of policy.

3.3.1 The Filing of Claims

Aside from cases of sheer fraud, claims will not be forthcoming unless a property owner (1) notes that something has been damaged, (2) attributes this damage to sonic booms, and (3) decides to file a claim. These three factors together determine the rate at which claims will be forthcoming.

How are they related to the booms themselves? According to the model of true damage presented above, the steady-state rate of all damage (including non-boom damage represented, in the model, by the term B) has nothing to do with booms as such. Booms enter the picture only in that they replace some other cause of breakage. In addition, they can cause an initial period of damage in excess of the steady-state natural rate. Hence claims will be forthcoming at a rate determined by attribution and action.

In a world of perfect knowledge, attribution of damage to sonic booms is associated with "true" sonic boom damage* only and may vary weakly or strongly with boom intensities,

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*We may define true sonic boom damage as breakage occurring at the same moment as a boom.

as represented by the alternatives provided for in Models I and II above. In the real world, however, claimants have perfect knowledge only rarely. Unless a claimant observes an item breaking simultaneously with a boom, he is forming a judgment in attributing damage to the boom. A typical home has six or seven rooms and is occupied by perhaps one or two adults during daytime hours, so that most damage must occur unobserved.

Some people, no doubt, form from what they hear or read the fixed opinion that sonic booms do or do not cause a certain type of damage. But the judgment of most is probably affected by their own observations of walls and windows shaking or of dishes rattling in cupboards as the boom strikes their home. As is indicated in Section 5, structural response to booms is roughly proportional to the overpressures. Hence we would expect that booms of greater magnitude will make more of an impression on people and that they will attribute a higher proportion of damage to booms of greater intensity. Nothing further can be deduced about the form of the relationship of attribution rates to boom intensity, except that the former have the natural upper limit of 100 percent.

Whether boom frequency affects attribution rates is another question. The chances of observing damage occurring simultaneously with a boom are greater for frequent booms, and this should be reflected in some increase in the attribution of damage to booms.

Lastly, we must consider whether a potential claimant who has observed damage and attributes it to the boom will go to the trouble of filing a claim. The "cost" of filing is the trouble of filling out a form and of receiving a claims investigator, and possibly of paying a contractor or repairman for an estimate of the extent of damage. These are quite small, but so may be the prospective gains, especially if it is known that a tough adjudication policy is being followed. We would expect that potential claimants will be less likely to file a claim involving slight damage (e.g., an ordinary pane of window glass) than they would be to file a more substantial claim (e.g., plate glass or thermal glass). In Oklahoma City, about 70 percent of all claims were in the \$100 to \$1,000 range (see Table 3-1).

TABLE 3-1

DISTRIBUTION OF OKLAHOMA CITY DAMAGE CLAIMS BY AMOUNT
(based on 10 percent sample)

Range	Percent of Claims
\$0.01 - 9.99	2
10 - 19.99	4
20 - 49.99	5
50 - 99.99	8
100 - 199.99	18
200 - 499.99	32
500 - 999.99	20
1000 - 1999.99	7
\$2000 and over	4
	100

Figure 3-1 below, suggests that action (as represented by telephone calls complaining of damage or annoyance) is quite variable and reflects, in part, such social factors as the effect of news releases, some of which were identified by FAA personnel as the probable causes of the various occasions of peak activity. The lower line in Figure 3-1 represents the estimated dates of breakage associated with claims subsequently filed. The peaks of this line always occur on the first and fifteenth of the months, indicating that claimants often do not recall the exact date of breakage and, instead, use the first and fifteenth as proxies for vague recollections. This suggests that the decision to file a claim is often not made until enough time has passed to permit this lapse of memory.

Table 3-2 provides additional evidence regarding the uncertainty of attribution. It lists claims filed by September 30 and attributed to days on which no flights, or fewer than six flights, took place. (We have omitted the first week of February.) Even if we omit from consideration the weeks including the first or fifteenth of the month (as being unreliable data), we note that the three remaining days on which no flights occurred were blamed for 23 incidents, compared to a total of 39 incidents as calculated at the average daily rates for the rest of those weeks. The six remaining days on which two to five flights occurred had 47 incidents attributed to them, compared to a total of 52 incidents, as calculated at the average daily rates for the rest of those weeks, whereas we would have expected that day-to-day fluctuations in true sonic boom damage would be proportional to day-to-day fluctuations in the frequency of

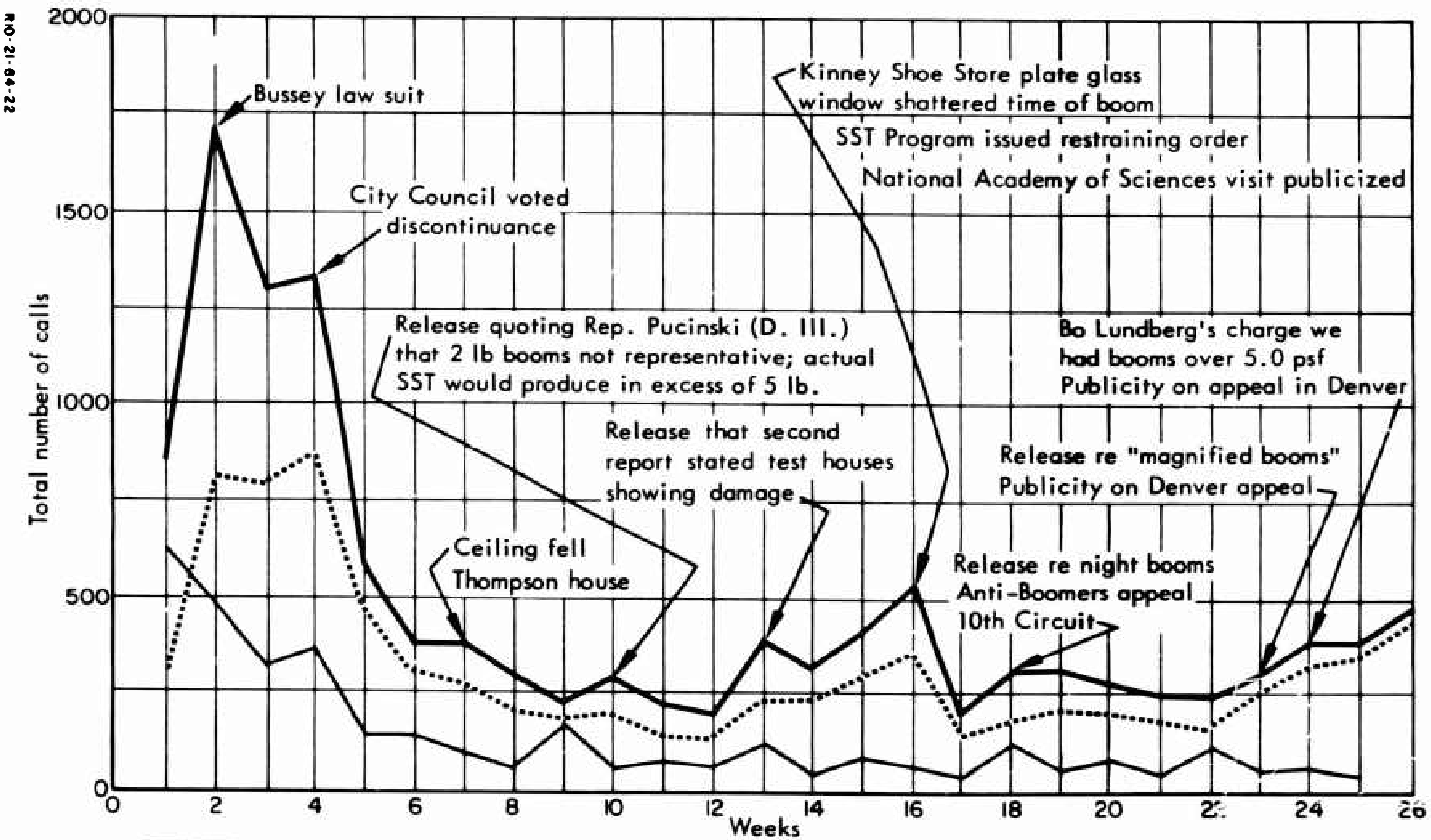
TABLE 3-2

OKLAHOMA CITY DAMAGE CLAIM INCIDENTS
FOR SELECTED DAYS
(for claims filed by September 30, 1964)

		No. of Incidents		
Date	No. of Booms	That Day	Rest of That Week	Per Day
2/12[a]	4	48	447	64
2/25[a]	0	43	317	45
3/4	2	14	120	20
3/8	0	14	120	20
3/9	4	16	133	19
3/19	0	6	76	11
3/25	5	7	47	8
3/29	0	3	47	8
4/2[a]	4	12	145	24
4/4[a]	0	3	145	24
4/15[a]	4	39	27	4
4/22	4	7	38	6
4/26	4	8	38	6
5/10	4	8	42	6
5/13[a]	0	6	28	5
5/15[a]	4	54	28	5
6/23	5	3	41	6

[a]Weeks including the first or fifteenth of the month

RIO-21-64-22



TOTAL CALLS	830	1711	1278	1324	600	390	379	282	242	290	217	192	407	321	410	540	210	318	327	282	249	242	304	398	393	458
ALLEGED DAMAGE CALLS	261	809	783	889	481	297	276	201	185	201	142	137	247	242	306	377	138	188	216	210	187	170	259	332	350	448

——— = Damage claims filed through Sept. 30 by week of incident.

Note: Includes some duplicate calls.

FIGURE 3-1 Weekly Telephone Calls and Damage Claims During Oklahoma City Test Program

booms. (Day-to-day fluctuations should not be confused with the equilibrium damage rates corresponding to alternative boom frequencies.)

3.3.2 Investigating Sonic Boom Damage Claims

A claims investigator's function is to inspect the damage, to estimate the cost of repairing it, and to assess its causation. The job is simple if there is an obvious cause other than sonic booms, such as impact marks indicating that a pane of glass was broken by a missile. But beyond that, it becomes a matter of looking for other probable causes, such as settling foundations or heavy truck traffic.

In past investigations of sonic boom damage claims, much importance has been attached to determining the date of the damage and also to determining whether similar, but older, damage was also present. Damage which antedated the booms or which was of the same sort as pre-existing damage (e.g., old plaster cracks) could readily be ascribed to other causes. This same consideration will, no doubt, be important in assessing damage during the initial period of SST operations, but will diminish in importance as these operations become a historical constant.

3.3.3 Adjudicating Sonic Boom Damage Claims

After a claim has been presented and investigated, a decision must be made to deny it or to approve and pay it, in full or in part. The disadvantages of paying a claim are that it costs money to do so and that it may encourage additional claims to be filed, by the same claimant as well as by others who hear of the payment. The disadvantages of not paying claims are the possibility of subsequent legal action by disgruntled claimants and the loss of goodwill. The latter is particularly significant in that it may translate itself into political pressure for the suppression or restriction of supersonic operations.

In striking a balance between paying too much or too little, personal factors may play some role. Some claimants command more public support than others and are therefore more difficult to turn away. Repetitive claimants may appear who file claims year after year and who, once recognized as such, may be refused, time and again, thereby saving many payments while offending only one claimant. Lastly, insurance companies, who would appear as subrogate claimants, may be refused through an extension of this principle.

On the whole, though, most of the weight of adjudication policy must be expressed in terms of the impersonal characteristics of the claim. What degree of positive evidence and what absence of negative evidence shall be required of a given type of claim for it to be paid in whole or in part?

[redacted]

On the principle of buying goodwill when it is cheap, small claims may be approved under more lenient standards than large ones. In dealing with large claims, the most rigorous standard of proof would be to require disinterested eyewitnesses to the coincidence of boom and breakage. Even where this is provided, the claim may be denied, under a severe adjudication policy, or paid only in part, on the grounds that the sonic booms were not the ultimate cause of the breakage, but only served to "trigger" a breakage that would have promptly occurred anyhow. (We return to this theory in a subsequent paragraph.)

More payments buy more goodwill, but how much they buy and how much is needed are difficult psychological and political questions. The adjudication policy normally followed by the Air Force results in about 40 percent of all claims being paid, in whole or in part, in amounts ranging to $1,000 per claim (actually, there has been a handful of slightly larger payments) but averaging around $100 (see Table 3-3). In Oklahoma City, however, only about one in thirty claims was paid (aside from an initial group that was more favorably disposed of) at an average of about $50 per claim. Assuming that it costs over $50 to handle such claims (this

TABLE 3-3

US AIR FORCE SONIC BOOM DAMAGE-CLAIMS EXPERIENCE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		Claims Approved			Amounts Approved			
Fiscal Year	Claims Received	No.	percent of (1)	Amounts Claimed, $	Total, $	per (1), $	per (2), $	per (4)
1956	36	21	0.58	12,220	1,914	53	91	0.16
1957	372	286	0.77	157,100	18,908	51	66	0.12
1958	522	235	0.45	196,216	39,519	76	168	0.20
1959	632	243	0.38	285,182	21,356	34	87	0.07
1960	681	227	0.33	107,768	20,263	30	89	0.19
1961	1,146	527	0.46	703,175	57,274	50	109	0.08
1962	3,092	1,451	0.47	990,483	132,370	43	91	0.13
1963	7,200	2,268	0.32	4,022,719	239,450	33	106	0.06
1964[a]	5,102	2,300	0.45	3,544,755	243,000	48	106	0.07
All	18,783	7,558	0.40	10,019,618	774,054	41	102	0.08

[a]preliminary figures for 1964

[redacted]

is discussed further below), and that claims denied produce no goodwill, it would seem that the Oklahoma City adjudication policy is an expensive way to buy very little goodwill.

An alternative method of limiting the expense of sonic boom damage claims would be to refuse to consider broad classes of claims, thereby saving their investigating and adjudicating costs, as well as the actual payments. If this were accompanied by a higher rate of payments on the remaining categories of claims, it might, conceivably, result in more goodwill at less cost.

We have, at this point, no way of assessing these various alternatives and note only that they exist. Whatever is done in the future, the Oklahoma City experience provides a basis for extrapolation, with suitable adjustments for changes in policies. We turn, therefore, in the next section, to a description and analysis of this experience.

3.4 DAMAGE CLAIMS EXPERIENCE

3.4.1 The Oklahoma City Data

During the 26 weeks from February 3 through July 30, 1964 the FAA tested the response of Oklahoma City to sonic booms. On most days during this period, eight supersonic flights were flown over the track described by the solid line in Figure 3-2. (Fewer were flown during the first week, and a few subsequent flights were also cancelled for various reasons. A few flights were performed over different tracks, as described in Section 5.)

The average overpressures and impulses recorded outside the three test houses shown in Figure 3-2 during each week are shown in Table 3-4, as are averages and standard deviations (σ) for the entire period. The averages vary from week to week, partly because of random atmospheric factors but also because of differences in flight altitude and aircraft type and speed. During the first few weeks, booms were purposely kept moderate, to let the public get accustomed to them. In mid-May F-101 aircraft were substituted for F-104 aircraft, but flown at higher altitudes to keep booms at about the same overpressure level in most of Oklahoma City. Nevertheless, the increase in flight altitude caused a significant increase in overpressures in areas which, like Test House 4, were relatively far removed from the flight track. Also, the impulse measure of boom intensity doubled, in relation to the overpressures, due to the larger size of the F-101 aircraft.

Claims filed by the public are tabulated in Table 3-5. (Column 9 of that table is repeated in Table 3-4 under the heading "Prompt Damage Claims.") The first group of columns of Table 3-5 identifies claims filed "through" September 30. (Actually about 80 claims which were filed during this period did not come to our attention in time to be included in these columns) These claims were identified as to location ("Area 4," as shown in Figure 3-2, consisting of Midwest City, Del City, and Census Tracts 54, 72 A - C, and 73 and located about the same distance from the flight

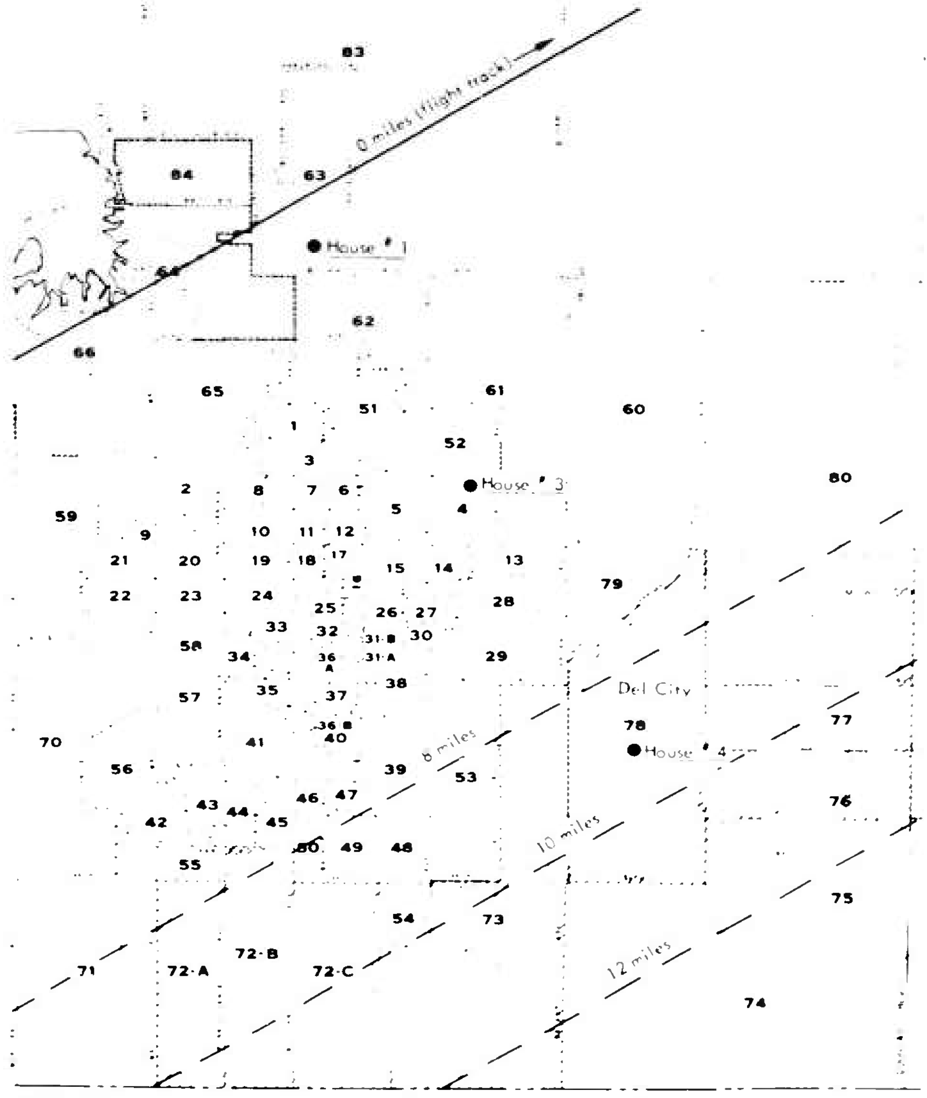


FIGURE 3-2 Map of Oklahoma City Area

TABLE 3-4

OKLAHOMA CITY SONIC BOOMS AND DAMAGE CLAIMS

Week	Through	Avg. Boom Overpressure, psf			Impulse, lb-sec/ft^2			Prompt Damage Claims
		House 1	House 3	House 4	House 1	House 3	House 4	
1	2/9	0.92	0.83	0.63	0.025	0.022	0.016	483
2	2/16	1.11	1.09	0.74	0.028	0.024	0.017	412
3	2/23	1.19	1.08	0.72	0.028	0.023	0.017	276
4	3/1	1.06	1.11	0.88	0.025	0.024	0.018	245
1 - 4	—	1.07	1.03	0.74	0.027	0.023	0.017	1416
5	3/8	0.97	0.96	0.74	0.022	0.022	0.018	120
6	3/15	1.16	1.28	0.89	0.024	0.027	0.020	120
7	3/22	1.18	1.34	0.86	0.023	0.026	0.018	70
8	3/29	1.14	1.30	0.94	0.025	0.028	0.022	49
5 - 8	—	1.11	1.22	0.86	0.024	0.026	0.020	359
9	4/5	1.16	1.17	0.83	0.025	0.024	0.017	105
10	4/12	1.25	1.47	1.00	0.026	0.030	0.021	51
11	4/19	1.11	1.36	0.81	0.025	0.024	0.019	56
12	4/26	1.12	1.13	0.85	0.024	0.023	0.019	54
9 - 12	—	1.16	1.28	0.87	0.025	0.025	0.019	266
13	5/3	1.15	1.33	1.11	0.025	0.027	0.024	103
14	5/10	1.21	1.21	0.90	0.025	0.026	0.021	49
15	5/17	1.12	1.14	0.94	0.031	0.028	0.026	89
16	5/24	1.22	1.33	1.26	0.050	0.049	0.048	73
13 - 16	—	1.18	1.25	1.05	0.033	0.033	0.030	314
17	5/31	1.16	1.37	1.10	0.048	0.049	0.045	44
18	6/7	1.44	1.66	1.30	0.056	0.052	0.043	128
19	6/14	1.40	1.70	1.42	0.046	0.053	0.046	52
20	6/21	1.42	1.76	1.44	0.046	0.051	0.047	89
17 - 20	—	1.36	1.62	1.32	0.049	0.051	0.045	313
21	6/28	1.69	1.76	1.56	0.058	0.052	0.049	50
22	7/5	1.52	1.62	1.42	0.058	0.043	0.050	126
23	7/12	1.58	1.52	1.27	0.060	0.053	0.045	72
24	7/19	1.80	1.65	1.43	0.060	0.053	0.051	82
21 - 24	—	1.65	1.64	1.42	0.059	0.053	0.049	330
25	7/26	1.14	1.43	1.18	0.044	0.052	0.048	53
26	7/31	1.13	1.34	1.40	0.040	0.050	0.047	178
1 - 26	—	1.26	1.33	1.08	0.037	0.037	0.032	3229
	—	0.40	0.59	0.53	0.0051	0.0048	0.0054	—

[redacted]

TABLE 3-5

OKLAHOMA CITY DAMAGE CLAIMS BY WEEK OF INCIDENT

		Filed through September 30										
			Area 4		Valid Claims			Semi-valid		Filed	
Week No.	Through	(1) Total	(2) No.	(3) Percent of Total	(4) No.	(5) Percent of Total	(6) $ Paid	(7) No.	(8) $ Paid	(9) Within 18 Wks.	(10) Through Nov. 8
1	2/9	624	—	—	15	—	664	57	3845	483	670
2	2/16	495	—	—	6	—	145	30	1774	412	502
3	2/23	319	—	—	12	—	264	6	423	276	322
4	3/1	360	—	—	6	—	184	1	86	245	398
1 - 4	—	1798	162	9.0[a]	39	2.2	1257	94	6128	1416	1892
5	3/8	148	17	—	5	—	269	—	—	120	151
6	3/15	149	11	—	—	—	—	—	—	120	163
7	3/22	82	4	—	3	—	215	—	—	70	82
8	3/29	57	5	—	2	—	136	—	—	49	58
5 - 8	—	436	37	8.5	10	2.3	620	—	—	359	454
9	4/5	160	12	—	5	—	87	—	—	105	183
10	4/12	54	6	—	—	—	—	—	—	51	54
11	4/19	66	7	—	1	—	14	—	—	56	72
12	4/26	53	3	—	—	—	—	—	—	54	56
9 - 12	—	333	28	8.4	6	1.8	101	—	—	266	365
13	5/3	121	11	—	3	—	79	—	—	103	154
14	5/10	50	6	—	3	—	119	—	—	49	55
15	5/17	88	8	—	5	—	371	—	—	89	97
16	5/24	72	5	—	6	—	784	—	—	73	78
13 - 16	—	331	30	9.1	17	5.1	1353	—	—	314	384
17	5/31	44	5	—	1	—	70	—	—	44	44
18	6/7	117	13	—	3	—	179	—	—	128	149
19	6/14	50	4	—	6	—	391	—	—	52	53
20	6/21	78	7	—	3	—	53	—	—	89	91
17 - 20	—	289	29	10.0	13	4.5	693	—	—	313	337
21	6/28	44	—	—	6	—	170	—	—	50	50
22	7/5	101	7	—	2	—	141	—	—	126	126
23	7/12	61	4	—	2	—	84	—	—	72[a]	70
24	7/19	63	2	—	2	—	117	—	—	82[a]	78
21 - 24	—	269	13	4.8	12	4.5	512	—	—	330	324
25	7/26	45	4	—	5	—	238	—	—	53[a]	50
Later	—	92	8	—	2	—	59	—	—	178[a]	142
All	—	3593	311	8.7	104	2.9	4833	94	6128	3229	3948

[a]Estimated.

[redacted]

track as Test House 4, was distinguished from all other locations) and as to subsequent disposition. The last two columns were based on a later and more complete claims record and show claims filed through November 8. (It is possible that a few claims filed in late October or early November have not yet come to our attention.)

The claims data have been tabulated by date of "incident," meaning the date on which the damage was said to have occurred. In some cases, these dates are averages of several dates reported by claimants and in others they, no doubt, reflect guesses or imperfect recollections. There were, for instance, several incidents reported for dates prior to February 3, the first day of supersonic booms. Furthermore, as mentioned previously, the number of incidents ascribed to the first and fifteenth days of the months is substantially greater than for adjoining dates. Hence caution must be used in making week-to-week comparisons of the number of claims. The final row is marked "Later," because it includes all incidents after July 26, including many ascribed to dates subsequent to the last boom.

3.4.2 Results of Damage Claims Investigation and Adjudication

Columns 4 to 8 of Table 3-4 give the results of the adjudication of the group of damage claims to which they pertain. Of the 1798 claims pertaining to February and March 1 incidents, 194 were promptly adjudicated under a relatively generous policy and 94 of these latter were approved in amounts averaging $65 per claim (leading to the indicated total of $6,128 for these claims which we have labeled "Semi-Valid.") The rest of the 3593 were adjudicated less generously, as indicated in Columns 4 and 5, only about 3 percent of them receiving approval, in whole or in part, in the average amount of $46 per claim.

Obviously, the cost of paying these claims was minor, amounting to less than $2 per claim filed, if we omit the first group of "Semi-Valid" claims. But these claims nevertheless involved substantial effort and expense on the part of claims investigators and of the Air Force legal personnel charged with adjudicating them. The claims investigators, working under FAA contract, received $30.50 per investigation.* In order to obtain a prompt view of the damage all reports of damage (excluding some cases in which written confirmation of a telephone call could not be obtained and excluding a few trivial ones of less than $7.50) were investigated at the above cost per investigation, and since there were about two reports of damage for every subsequent claim filed, the investigating costs really amounted to about $61 per claim filed.

*The contract price included the manning of a telephone center to receive calls complaining of damage or annoyance, and hence covers the "receiving" of claims, as well as the actual investigation.) We also asked various insurance experts for their estimates of the cost of this work. Their figures ranged from $20 to $200 per claim.

Adjudication of these claims required about 1 1/2 hours of time on the part of Air Force legal officers, plus secretarial time and office space. If we assign a value of \$30 to this function, we arrive at a total investigating and adjudicating cost of \$91 per claim filed for the Oklahoma City experiment, or about \$93, if we include the actual payment of claims at the post-February rate.

However, we feel that the manning of a telephone center and the investigating of so many potential claims that were not subsequently filed was a special feature of the Oklahoma City situation. We believe that future damage claims can be handled at a lower cost (after, perhaps, an initial period of several months that may follow the Oklahoma City pattern). We shall therefore use the smaller figure of \$60 per claim for the estimated cost of receiving, investigating, adjudicating, and paying future damage claims.

For a number of reasons, we think it probable that there will be little litigation in connection with sonic boom damage claims and that they will generally be disposed of administratively, by the airlines or by their insurers or by a government agency, much as they were in Oklahoma City. First, there has so far been no litigation in connection with Oklahoma City damage claims, although there was one unsuccessful attempt to seek injunctive relief. Second, as pointed out in Section 6, there are substantial questions of the existence, under present law, of liability for damage caused by non-negligent operations (and we expect airline operations to be generally non-negligent). Third, there are also substantial difficulties in the concept of sonic boom "causation" of damage (see Section 3.4.3). Finally, sonic boom property damage (at the boom intensities of transport operations) will rarely be large enough to justify substantial legal expenses on the part of claimants. We have therefore not considered it necessary to include, in our estimated cost per claim, an amount for court expenses.

3.4.3 The Concept of Trigger Damage

There are about 200,000 housing units in the Oklahoma City area, containing close to a million rooms and ceilings and several million walls and windows. (More than half of these had about the same boom magnitudes as House 3.) Whether we reduce the 5,000 or so claims that may eventually be filed to eliminate those which do not represent boom-connected damage or increase this number to reflect unreported boom-connected damage, we would still conclude that only a small fraction of the objects exposed to booms sustained damage "from" them.

Had only a small number of booms been produced, we might assert that the considerable geographic variability of overpressures which can result from even minor atmospheric disturbances resulted in breakage only of items in the most unfortunate locations, where overpressures were highest. However, with over a thousand booms along the same flight track, this hypothesis becomes untenable, for each location

will receive similar maximum overpressures. (Table 3-6 indicates the percentage of locations receiving various maximum overpressures, assuming a normal distribution with the mean and standard deviation of the observed overpressures at House 3. The Table is arranged in terms of multiples of standard deviations to be added to the mean to facilitate computation of maxima corresponding to other overpressure means or standard deviations.)

It therefore seems likely that items which actually did receive sonic boom damage were weaker than many other similar items and therefore contributed to the damage level.

TABLE 3-6

PROBABILITY OF ONE OR MORE BOOMS EXCEEDING $\bar{y}$ PLUS M MULTIPLES OF σ_y

M	$\bar{y}$,[a] psf	Probability of Exceeding y with n Flights: n 1	n 10	n 100	n 1000	n 10,000
0	1.33	0.50	1.00	1.00	1.00	1.00
0.5	1.62	0.31	0.97	1.00	1.00	1.00
1.0	1.92	0.16	0.82	1.00	1.00	1.00
1.5	2.22	0.07	0.50	1.00	1.00	1.00
2.0	2.51	0.02	0.21	0.90	1.00	1.00
2.5	2.80	0.01	0.06	0.46	1.00	1.00
3.0	3.10	—	0.01	0.13	0.74	1.00
3.5	3.40	—	—	0.03	0.21	0.90
4.0	3.69	—	—	—	0.02	0.21

[a] Based on an average psf ($\bar{y}$) of 1.33 and σ_y of 0.59 over 26 weeks at test house 3.

That is to say, sonic booms appear to be contributory causes, not sole causes of damage.

But there are degrees of contributory causation, reflected in the answer to "How long would the item have lasted in the absence of sonic booms?" Our only evidence on this point is the disparity between the initial and subsequent rates at which sonic boom claims were forthcoming. From this we infer a high ratio of sonic boom damage to other damage or removal (C/B in the model presented in Section 3.2). This means that vulnerable items would last longer, without the sonic booms, but it does not mean that items in general would last much longer. If the rate, A, at which items enter the vulnerable category is low, relative to the population of all items (vulnerable or not), then the average life of all items is mainly determined by how long they remain non-vulnerable, not by how soon they break after they become vulnerable. Whether they break very promptly, through sonic boom effects at the rate CN, or just promptly through other causes, at the rate BN, might then be judged unimportant.

An interesting calculation can be performed if we neglect the fact that there are different types of breakable items and think in terms of a single representative type. In the process of moving from the initial impact situation to the steady-state situation, the number of breakable items is reduced from N_o to N_y and of these $\frac{rf(y)}{1 - rf(y)}$ or about six

out of seven (according to our estimate of $rf(y)$) are broken by sonic booms. If we take the difference between the 1775 claims in the first 8 weeks and disregard claims filed more than 18 weeks after the incident and the 580 claims in the next 8 weeks (which, we assume, were generated at the steady-state rate) we find that 1195 claims resulted from the initial excess of breakable items, suggesting that the difference between N_o and N_y was 1394 items (199 of which broke through causes other than booms). With this difference and with a ratio of 7 to 1 between N_o and N_y it follows that $N_o = 1626$ and $N_y = 232$. Since the steady-state weekly rate of sonic boom damage (72 claims per week, based on 580 claims) is the product of $N_y = 232$ and rC, then the latter term must equal 72/232 or 0.31, and the weekly rate of ordinary breakage B would be 1/6 this rate or 0.05. The rate A at which breakable items enter the boomed population is, of course, the same as the steady-state rate of all breakage, or 7/6 this rate (72) of sonic boom breakage (i.e., 84 items per week).

Comparing the generation rate of 84 with the estimated values of 1626 for N_o and 232 for N_y, it would seem that a typical breakable item lasts 1626/84 or 19 weeks in the absence of booms and 232/84 or 3 weeks with the booms. Booms, according to this model and these figures, are therefore estimated to reduce the life of defective items by 16 weeks.

The above describes, in a somewhat roundabout way, the theory of "trigger damage," to the effect that only the exact timing of the breakage is determined by the sonic boom "trigger." It is an extreme version of the contributory causation theory and one which often prompts adjudicators to reject damage claims.

3.4.4 The Impact Phenomenon and the Effect of Boom Frequency

According to the models of real sonic boom damage described in Section 3.2, damage rates should decline, from the initial rate, to a lower steady-state rate. The claims filed in Oklahoma City did, indeed, taper off drastically, although this could be ascribed to social factors or to the attribution of pre-existing damage to the first weeks of booms.

If we compare the "prompt claims" filed during the second week (which was the first full week of operations) with those filed during the seventh week, we get a ratio of 412/56 or a value of 7 for the quantity $1 + rf(y)$ in Eq. 14. (We selected two weeks which included the 15th of the month. Other estimates could be based on other pairs of figures, but they would not be sufficiently different to disturb our conclusions.) Using this value for $1 + rf(y)$, we can estimate $rf(y)$ to be 6, and

$$f(y) = \frac{6}{7.2} = 0.83 \qquad (16)$$

for r = 7.2 daily booms. The implications of this estimate for higher or lower boom frequencies are apparent from the steady-state equation (Eq. 11), from which (with an obvious change of notation)

$$\bar{D}_{r,y;r,y} = \frac{0.83}{1 + 0.83}\, g(y) \qquad (17)$$

for booms of intensity y, where g(y) is the maximum steady-state damage for this intensity. Since this works out to 0.7 [g(y)] for 7.2 booms per day, this estimate suggests that the Oklahoma City rate of claims would not have been appreciably higher for much larger boom frequencies.

This conclusion cannot be directly tested, since higher boom frequencies have not yet been experienced. In order to reduce the risk of underestimating future claims, we have used in Section 4 the more conservative figure of 0.16 rather than the estimate of 0.83 based on our model of true sonic boom damage. This revision may be viewed as an attempt to make some allowance for the possibility, discussed in Section 3.3, that boom frequency may affect the attribution and action rates, possibly to a greater extent than they affect true damage rates.

3.4.5 The Effect of Sonic Boom Intensity

It is noted in Section 5 that the overpressure measure of sonic boom intensities is more closely related to structural response and, presumably, damage, than the impulse measure. The Oklahoma City claims experience shown in Table 3-3 lends some support to this thesis. Impulses doubled, during the 15th week of booms, while overpressures remained about the same for over two weeks and then increased, together with further increases in impulses.

If we compare the 110 claims originating in the 11th and 12th weeks (low overpressures and impulses) with the 117 claims from the 16th and 17th weeks (low overpressures, high impulses) we find support for the position that damage rates do not vary strongly with impulses, for given overpressures. The effect of changes in overpressures cannot be discerned from these data, since the variation in overpressures was rather moderate and since variations in claims due to other factors played too large a role.

3.4.6 Future Damage Claims

At this point, it is difficult to predict what damage claims will be filed when supersonic transports become operational on airline routes. Since this will depend in part on how such claims are adjudicated, it becomes a matter of policy. We have no basis in fact for estimating the results of very frequent operations. Our estimate of 0.16 for f(y), in place of the higher figure that emerges from our model of true sonic boom damage and from a comparison between initial and steady-state rates of claims, is no more than an unsupported opinion.

Finally, we do not yet know how many claims are still to be filed in connection with the Oklahoma City flights.

Comparing column 1 of Table 3-4 with column 10, we note that claims are still being filed at a substantial rate. (February and March claims were largely filed promptly, but the rest showed no sign of tapering off as of November 8, the cut-off date). Since claims are accepted until two years after the date of an incident, a substantial number could still be filed. Assuming, however, that the additional claims to be filed will amount to 3 times the number filed between September 30 and November 8, the total will finally amount to about 5000 claims and the steady-state rate (after February and March) will be about 500 per month. On this basis, we estimate that future steady-state claims by persons experiencing the same overpressures as the 600, 000 residents of the Oklahoma City area will be filed at the monthly rate of $\frac{0.16r}{1 + 0.16r} \times 0.00154$ per person per month. Multiplying this by our estimated cost of $60 per claim and converting to a per-day basis, we get $\frac{0.16r}{1 + 0.16r} \times \$0.00308$ per person per day as the estimated steady-state cost associated with overpressures similar to those experienced in Oklahoma City.

4

ROUTE ANALYSES

4

ROUTE ANALYSES

This section considers the reduction in claims costs that could be realized by various modifications of a basic SST route configuration.

After a brief description of the sonic-boom path (Section 4.1), the method used here for estimating SST claims costs is described (Section 4.2). The claims costs for operating the SST in the US over a given route network are then derived and the cost-effect of modifying the initial route network is determined (Section 4.3). Finally, the projected claims costs for global SST operation are discussed (Section 4.4).

4.1 THE SST SONIC BOOM PATH

The SST sonic boom starts approximately 100 n mi out from the departure airport and ends approximately 175 n. mi. short of the destination airport. Because of the refraction in the atmosphere, the SST boom "cuts off" about 25 n. mi. on each side of the flight track. Since all city pairs will be flown in both directions, the ground track between a pair of cities will be boomed starting 100 n. mi. from each city by outgoing flights. Although the segment between 100 and 175 n. mi. will not be boomed by incoming flights, outgoing flights during acceleration will produce high overpressures in this region.

4.2 METHOD OF ESTIMATING SST CLAIMS COSTS

SST claims costs were estimated from the Oklahoma City results largely by extrapolating those results to more frequent flights and to the total US population exposed to booms. Such a procedure assumes that certain aspects of the Oklahoma City tests will not change signifi-antly for SST operations. Before describing the specific method of estimation used in this study, we will discuss briefly the validity of these assumptions.

First, we have not attempted to vary claims costs along the flight track of the SST as a function of overpressure. As discussed in Section 3, we did not discover a correlation between overpressure and claims costs within the range of overpressures experienced during the Oklahoma City test program. This range of overpressures was representative of those expected of the SST.

Second, we beli.ve that the Oklahoma City sonic boom environment was generally representative of the SST boom

[redacted]

environment. The discussion in Section 3 indicates that claims for damage to ground structures comprise by far the largest category of claims. Based on the Oklahoma City data, the major cost of these claims is in administrative handling; actual payments are relatively minor. Therefore, the Oklahoma City claims data are approximately valid for SST routes only insofar as persons boomed by the SST attribute similar structural damage to the SST, even though the damage may not have actually been caused by the SST. For example, even though actual damage caused by sonic booms in two areas was identical, the cost (mainly administrative) of claims in one area could be much higher if structures in that area were suffering damage from other causes which were incorrectly attributed to the SST.

Finally, we feel that the Oklahoma City claims data are representative of the situation that will exist in the US and Canada during SST operations. However, they are almost certainly not representative of the situation that will be found in other areas of the world, particularly in areas with very different climatic conditions or level of economic development. Accordingly, we have made quantitative projections of future SST claims costs only for domestic routes; foreign routes have been examined only qualitatively. Since claims costs are more or less directly related to the number and value of buildings boomed, and since these are approximately proportional to the population boomed, we have used population as an indirect means of relating Oklahoma City claims costs to future SST claims costs.

Two pure theories for projecting SST claims cost emerge from the Oklahoma City tests. The data yielded by those tests, which included claims cost, number of people boomed, number of booms, and number of days during which booms occurred, suggest a "person-boom" theory and a "person-day" theory (See Figure 4-1). The person-boom theory assumes that claims costs are directly proportional to the number of times a given population is boomed. The person-day theory assumes that claims costs are constant per day irrespective of the number of booms, so long as the given population is boomed at least once per day.

Person-boom costs are expressed by the following equation, in which the factor of $60 per claim is based on Oklahoma City experience:

$$\frac{\$}{\text{person-boom}} = \frac{\$60 \times \text{number of claims}}{\text{number of persons boomed} \times \text{number of flights}}$$

With Oklahoma City data,*

$$\frac{\$}{\text{person-boom}} = \frac{\$60 \times 2500}{600{,}000 \times 1083} = \$0.000231$$

Person-day costs are expressed as follows:

$$\frac{\$}{\text{person-day}} = \frac{\$60 \times \text{number of claims}}{\text{number of persons boomed} \times \text{elapsed days}} ;$$

*The first month's data were not used, since they were not representative of the recurring cost (See Section 3).

[redacted]

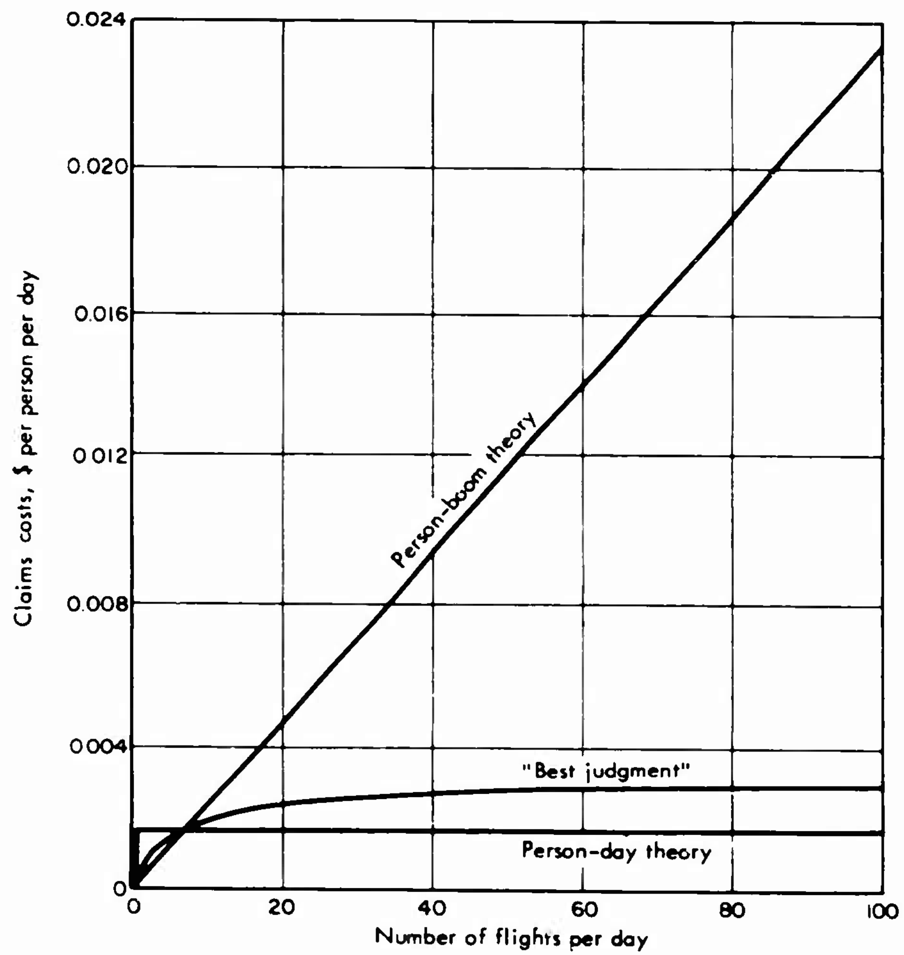


FIGURE 4-1 Claims Costs vs. Flight Frequency

which, with Oklahoma City data,

$$= \frac{\$\ 60 \times 2500}{600{,}000 \times 152} = \$0.00165$$

We believe that the person-boom theory is appropriate for a situation in which the total number of booms considered is sufficiently low (say, no more than 100) that only a fraction of the breakable items are actually broken by the booms. However, it is inappropriate as a description of the effects of the many flights characteristic of the Oklahoma City experiment and of future airline operations. For the latter, we consider a better approximation to be the person-day theory, according to which claims costs are constant per day, irrespective of the number of booms.

The person-day theory is based on the evidence that completely sound structures suffer virtually no damage from the SST level of overpressures, but that prestressed structures can be damaged by the SST, or that damage to them by other causes can be attributed to the SST. Accordingly, once the prestressed structures in an area have been damaged, no further damage will occur until more prestressing takes place. Hence, if an area is boomed every day, the level of claims will be mainly determined by the rate at which structures become prestressed rather than by the number of booms.

We are convinced, however, that there is some relation (although not a proportional one) between frequency of booms and damage claims. As discussed in Section 3, this must be expected since there are causes other than booms that may break boom-vulnerable items. With higher boom frequencies, the chances of a sonic boom of sufficient

intensity hitting such an item before it breaks through some other cause are increased. Moreover, it seems reasonable to expect that high boom frequencies will incline the boomed population to attribute to booms damage from unknown causes.

The "best-judgment" curve in Figure 4-1 describes our best estimate of the combined effect of these factors. Best-judgment costs are based on the mathematical model described in Section 3; they are expressed as follows:

$$\frac{\$}{\text{person/day}} = 0.00308 \left(\frac{0.16r}{1 - 0.16r}\right),$$

where

r = number of flights per day.

The best-judgment costs for SST operations for one year in the US were derived from Figure 4-1 by first calculating the person-boom and person-day costs, and then following these four steps:

(1) The ratio of claims cost calculated by the person-boom method to costs calculated by the person-day method was determined $\left(\frac{\$199,900,000}{\$\ 80,000,000} = 2.5\right)$.

(2) The average flight frequency was determined by the point at which the person-boom and person-day lines are in the same ratio as the calculated claims costs (at 17.7 flights per day: $\left(\frac{0.0041}{0.00165} = 2.5\right)$.

(3) The ratio of the best-judgment curve to the person-day value at the average flight frequency was determined

$$\left(\frac{0.00214}{0.00165} = 1.29\right).$$

(4) The person-day cost was multiplied by the ratio given in 3 above to obtain the best-judgment cost

(1.29 x \$80,000,000 = \$103,500,000).

The best-judgment cost represents our best estimate of annual SST claims cost.

4.3 ANALYSIS OF US SST ROUTES

The 52 US city pairs shown in Table 4-1 were used in calculating claims costs. These city pairs and the flight frequencies shown in Table 4-1 approximate the longer routes being flown nonstop by jet aircraft as of September 1964[1]. These routes were first laid out on great-circle tracks (Figure 4-2). The route distances and population boomed were then entered in Table 4-1. Population boomed was that population within a band 50 n. mi. wide starting 100 n mi from the departure and arrival airports. The population was determined from the 1960 census by county[2] and was then extrapolated to 1975 by using the ratio of the projected 1975 population[3] for the 48 conterminous states to the actual 1960 population $\left(\frac{234,375,000}{178,464,000}\right)$ Population boomed was determined both by individual route and for the total route network. Total route network population boomed

TABLE 4-1

US SST ROUTE-CONFIGURATION 1

(1) City Pairs[a]	(2) Nautical Miles, Subsonic, From 1st city	(3) Nautical Miles, Subsonic, From 2nd city	(4) Nautical Miles, Total	(5) Total Cost per Trip, $	(6) Frequency Both Ways, Flts./Day	(7) Airline Total Cost per year, $$10^6$$ (5)x(6)x365	(8) 1975 Pop. Boomed per Flt., 10^6 persons	(9) Yearly Claims Cost Person-Boom[b] Theory, $$10^6$$ 0.000231 x (8)x(6)x365
N. Y. C. -Miami	100	100	939	5,870	38	81.40	0.620	1.99
N. Y. C. -Seattle			2,096	10,030	4	14.66	7.220	2.44
N. Y. C. -San Fran.			2,222	10,550	26	100.00	20.800	45.70
N. Y. C. -L. A.			2,126	10,180	34	126.20	10.544	30.25
N. Y. C. -Anchorage			2,950	13,520	2	9.86	2.319	0.39
N. Y. C. -Houston			1,230	6,830	4	9.98	7.376	2.47
N. Y. C. -New Orleans			1,016	6,100	10	22.44	8.100	6.86
Wash. D C. -Seattle			1,987	9,640	4	14.09	10.340	3.49
Wash. D. C. -San Fran.			2,078	10,000	4	14.60	7.206	2.43
Wash. D. C. -L. A.			1,967	9,550	22	76.70	8.428	15.63
Miami-Chicago			1,033	6,200	16	36.20	5.970	8.06
Miami-San Fran.			2,239	10,660	2	7.77	5.345	0.89
Miami-L. A.			2,013	9,750	2	7.10	4.202	0.69
Chicago-Seattle			1,510	7,850	14	40.10	1.982	2.35
Chicago-San Fran.			1,578	8,100	32	94.40	2.241	6.05
Chicago-L. A.			1,496	7,800	50	142.60	1.872	7.90
Chicago-Anchorage			2,500	11,670	2	8.51	1.194	0.19
Seattle-L. A.			826	5,460	8	15.92	0.612	0.42
Seattle-Anchorage			1,261	6,970	8	20.34	0.197	0.13
Wash. D. C. -Miami			800	5,360	2	3.91	1.310	0.23
L. A. -Atlanta			1,665	8,400	2	6.13	3.420	0.58
L. A. -Boston			2,243	10,650	4	15.56	16.113	5.44
L. A. -Cleveland			1,757	8,880	10	32.12	4.132	3.47
L. A. -Dallas			1,065	6,330	20	46.20	0.662	1.12
L. A. -Detroit			1,690	8,520	4	12.46	10.044	3.39

(cont'd.)

TABLE 4-1

US SST ROUTE-CONFIGURATION 1—Continued

(1) City Pairs[a]	(2) Nautical Miles, Subsonic, From 1st city	(3) Nautical Miles, Subsonic, From 2nd city	(4) Nautical Miles, Total	(5) Total Cost per Trip, $	(6) Frequency Both Ways, Flts./Day	(7) Airline Total Cost per year, $10^6 (5)x(6)x365	(8) 1975 Pop. Boomed per Flt., 10^6 persons	(9) Yearly Claims Cost Person-Boom[b] Theory, $10^6 0.000231 x (8)x(6)x365
L. A. -Houston	100	100	1,198	6,72	10	24.53	1.777	1.50
L. A. -Kansas City			1,166	6,62	8	19.35	0.619	0.42
L. A. -Memphis			1,387	7,40	2	5.40	2.370	0.39
L. A. -New Orleans			1,435	7,58	4	11.08	3.840	1.30
L. A. -Des Moines			1,239	6,88	2	5.02	1.390	0.23
L. A. -Phila.			2,055	9,92	6	21.70	10.400	5.28
L. A. -St. Louis			1,350	7,280	12	31.87	1.558	1.58
San Fran. -Atlanta			1,830	9,020	2	6.58	3.180	0.54
San Fran. -Boston			2,322	11,000	2	8.03	13.176	2.24
San Fran. -Dallas			1,265	7,000	10	25.57	0.660	0.54
San Fran. -Houston			1,419	7,500	2	5.47	1.144	0.19
San Fran. -Phila.			2,158	10,30	2	7.51	10.670	1.81
San Fran. -St. Louis			1,487	7,780	2	5.68	3.270	0.54
Portland-Chicago			1,501	7,830	4	11.47	1.493	0.50
Portland-Minneapolis			1,213	6,800	4	9.94	0.765	0.27
Denver-Wash. D. C.			1,235	6,880	4	10.05	6.970	2.35
Denver-N. Y. C.			1,407	7,500	6	16.44	12.018	6.09
Dallas-N. Y. C.			1,185	6,700	16	39.10	6.490	8.75
Dallas-Wash. D. C.			996	6,000	10	21.90	3.840	3.24
Kansas City-N. Y. C.			952	5,900	4	8.61	10.230	3.47
Minneapolis-N. Y. C.			883	5,680	2	4.15	9.146	1.54
Detroit-Miami			1,000	6,030	2	4.40	5.410	0.93
Boston-Miami			1,084	6,370	4	9.29	0.028	0.04
Pittsburgh-Miami			876	5,630	6	12.32	2.650	1.35
Cleveland-Miami	↓	↓	935	5,850	2	4.27	3.500	0.58

(cont'd.)

[redacted]

TABLE 4-1

US SST ROUTE-CONFIGURATION 1—Continued

(1) City Pairs[a]	(2) Nautical Miles: Subsonic: From 1st city	(3) Nautical Miles: Subsonic: From 2nd city	(4) Nautical Miles: Total	(5) Total Cost per Trip, $	(6) Frequency Both Ways, Flts./Day	(7) Airline Total Cost per year, $$10^6$ (5)x(6)x365	(8) 1975 Pop. Boomed per Flt., 10^6 persons	(9) Yearly Claims Cost Person-Boom[b] Theory, $$10^6$ 0.000231 x (8)x(6)x365
Phila.-Miami	100	100	874	5,650	10	20.62	1.250	1.04
Houston-Wash. D. C.	↓	↓	1,039	6,200	2	4.53	3.950	0.66
					464	1,314.13	(132.800)[c]	199.93

[a] All routes direct.

[b] Yearly claims cost by the person-day theory = $0.00165 x 132,800,000 x 365 = $80,000,000.

[c] This number, which is the total number of people boomed, is not the sum of people boomed in each flight track; communities under more than one flight track were counted only once in arriving at this total.

is the total population subjected to any SST booms, but does not double count any areas overflown by more than one route. Where flights between US cities involved overflying Canada, the Canadian population boomed was included.

The yearly claims cost for each city pair was calculated on a person-boom basis. The yearly claims cost for the total network was found, on this basis, to be $199,930,000. The yearly claims cost for the total network using the person-day method was found to be $80,000,000. The ratio of these costs indicates that the average number of booms per day is approximately 17.7. Accordingly, best-judgment claims costs would be approximately $103,500,000, as explained at the end of Section 4.2.

Airplane operating costs for each route are also shown in Table 4-1. These costs are for the Boeing design

[redacted]

[redacted]

FIGURE 4-2 US Route—Configuration 1

[redacted]

of January 15, 1964. Figure 4-3 shows the direct and total operating costs for this airplane for the following conditions:

depreciation:	14 year
fuel:	11¢/gal
utilization:	3,000 hr/yr
TBO for engines:	3,000 hr
oil:	$12/gal

Indirect costs are as projected by Boeing.

The two techniques for reducing claims costs which we have studied are to fly circuitously (i.e., to avoid densely populated areas) or to fly subsonically for an extra distance at the beginning or end of the flight.* Figures 4-4 and 4-5 show the additional cost per nautical mile of these two techniques. The direct costs included in these figures are those estimated by Boeing. The additional indirect costs were projected by assuming that traffic carried and airplane utilization would remain constant. Therefore, an increase in block time, resulting from either circuitous routing or extra subsonic flight, would require a bigger fleet of aircraft. In examining the elements of indirect cost, we estimate that marginal indirect costs

*As discussed in Section 3, we did not discover a correlation between overpressure and claims costs within the range of overpressures experienced during the Oklahoma City test program. Therefore, we have not attempted to predict any reduction in claims costs as a result of flying at higher than optimum altitude (which will slightly reduce ground over pressure).

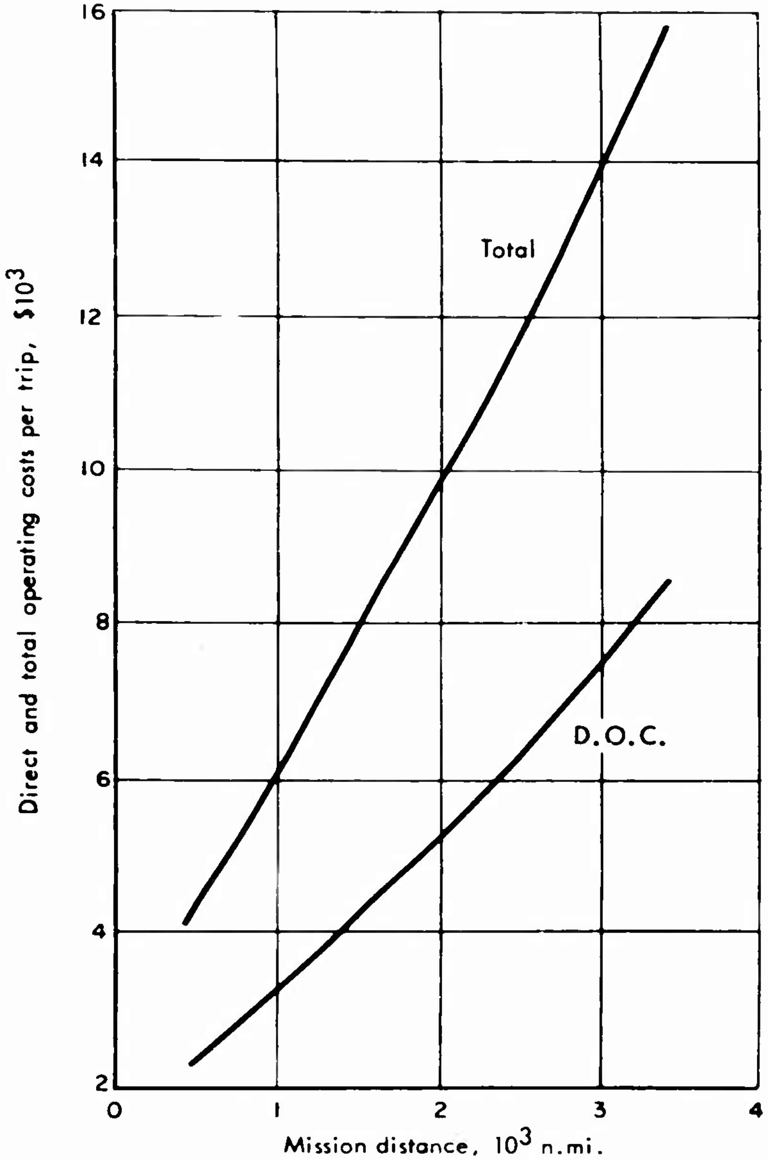


FIGURE 4-3 Direct and Total Domestic Operating Costs per Trip as a Function of Mission Distance

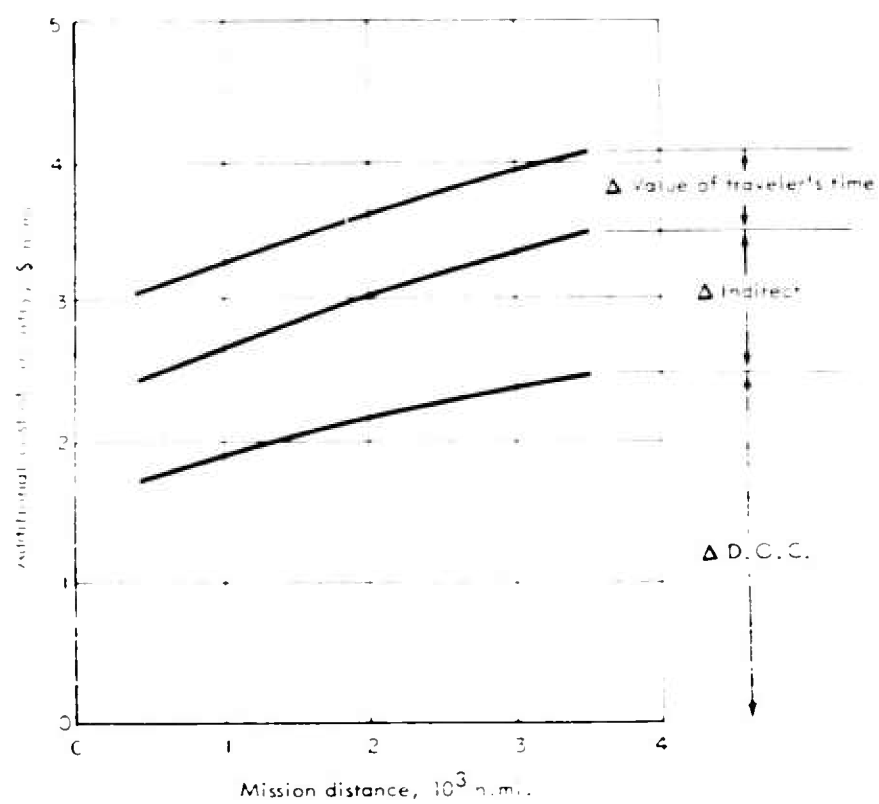


FIGURE 4-4 Additional Domestic Costs per Trip for Each Nautical Mile of Circuitous Flight (Normal Flight Profile)

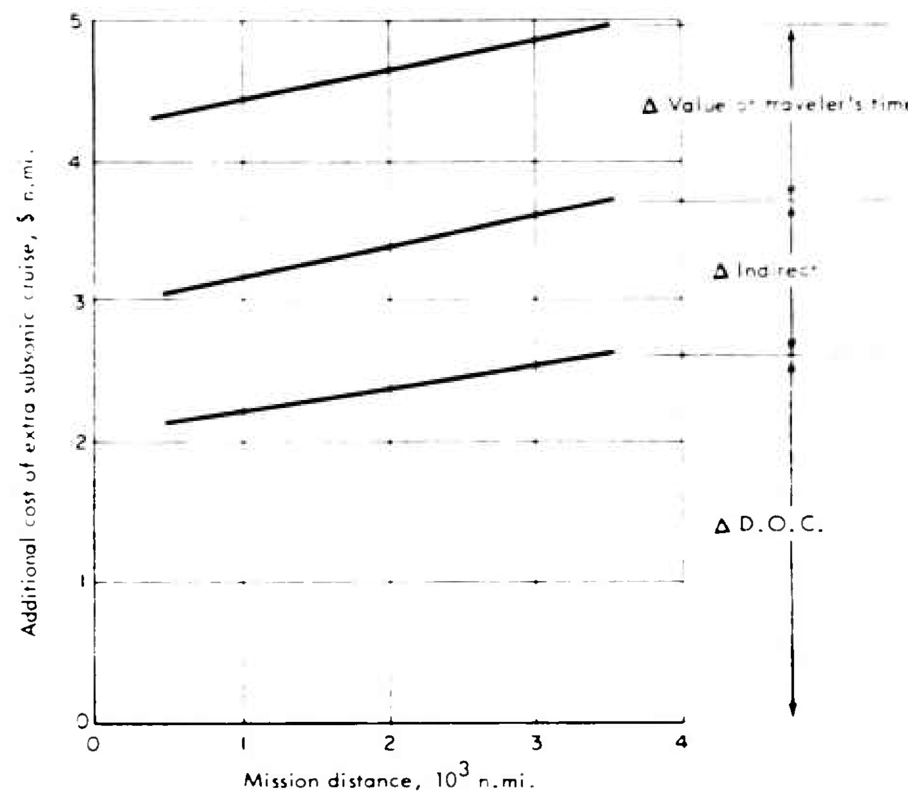


FIGURE 4-5 Additional Domestic Costs per Trip for Each Nautical Mile of Extra Subsonic Cruise Legs(s)

using these flight techniques would increase relative to direct costs at only half the normal rate shown in Figure 4-3.

In addition to the increase in airline operating costs resulting from these flight techniques, some account must be taken of the value of the loss in travelers' time. This loss was calculated on the basis of a 60 percent load factor (150 seats and 90 passengers) and a $10/hr value on a passenger's time. Sixty percent is representative of long-haul load factors. The value of a passenger's time is representative of the income of the average air traveler ($15,000 per year or $7.50 per hour based on a 2,000 hr work year) + 1/3 for business overhead. Accordingly, the upper curves of Figures 4-4 and 4-5 represent the total additional costs of flying circuitously or flying a more-than normal distance subsonically. The additional airplane costs for a mile of subsonic instead of supersonic cruise are only slightly more than for an extra mile of circuitry. However, the time loss is considerably more for the subsonic cruise technique, so that the loss due to the value of traveler's time is greater.

Based on the additional costs of Figures 4-4 and 4-5, tradeoffs between increased airplane operating costs and reduced ground damage costs are presented in Tables 4-2 through 4-9. The eight route configurations used in these analyses are shown in Figures 4-2 and 4-6 through 4-12. Starting from the all-great circle route configuration (Figure 4-2) the routes were cumulatively modified in the succeeding seven route configurations. Modified routes are denoted by dotted lines in Figures 4-6 through 4-12. The approach used was to successively reduce the total population boomed by the route network. This was accomplished by first changing those routes for which slight modifications would avoid centers of population relatively easily, and then superimposing other parallel routes in order to "uncover" the map. In this process, the population boomed on two routes (New York to Dallas and New York to New Orleans) was actually increased when the routes were modified. However, the total population exposed to boom was reduced by these modifications. Configurations 2 through 6 involved circuitous routing only. Configuration 7 involved extra subsonic flight on two routes to "uncover" urban areas between New York City and Washington, D. C. These routes were chosen to investigate the subsonic technique because they appeared to be the most suitable for this technique. Table 4-9 shows that this change was not nearly as profitable as the preceding five changes; the additional airplane costs more than doubled (from $1.71 to $3.61 million) and the reduction in best-judgment claims costs was not nearly doubled. However, best-judgment claims cost was reduced b $2.4 million, while the airplane cost was increased $1.9 million. With Configuration 7, most of the relatively simple changes had been accomplished. Configuration 8 was a major change designed to superimpose many of the East-West flights or segments of them.

FIGURE 4-6 US Route—Configuration 2

[redacted]

TABLE 4-2

US ROUTE-CONFIGURATION 2

Change from Configuration 1: Miami to San Fran. moved south to avoid New Orleans, Dallas & Ft. Worth

(1) City Pairs	(2) Nautical Miles, Subsonic, From 1st city	(3) Nautical Miles, Subsonic, From 2nd city	(4) Nautical Miles, Total[a]	(5) Total Cost per Trip, \$	(6) Frequency Both Ways, Flts./Day	(7) Airline Total Cost per year, $\$10^6$ (5)x(6)x365	(8) 1975 Pop. Boomed per Flt., 10^6 persons	(9) Yearly Claims Cost Person-Boom[b] Theory, $\$10^6$ 0.000231 x (8)x(6)x365
Miami-San Fran.	100	100	2,448	10,690	2	7.80	2.420	0.42
			(2,239)				128.700[c]	

[a]Number in parentheses indicates total mileage for Configuration 1.

[b]Yearly claims cost, person-day theory = \$0.00165 x 128,700,000 x 365 = \$77,500,000.

[c]Total 1975 population boomed (see footnote c, Table 4-1).

[redacted]

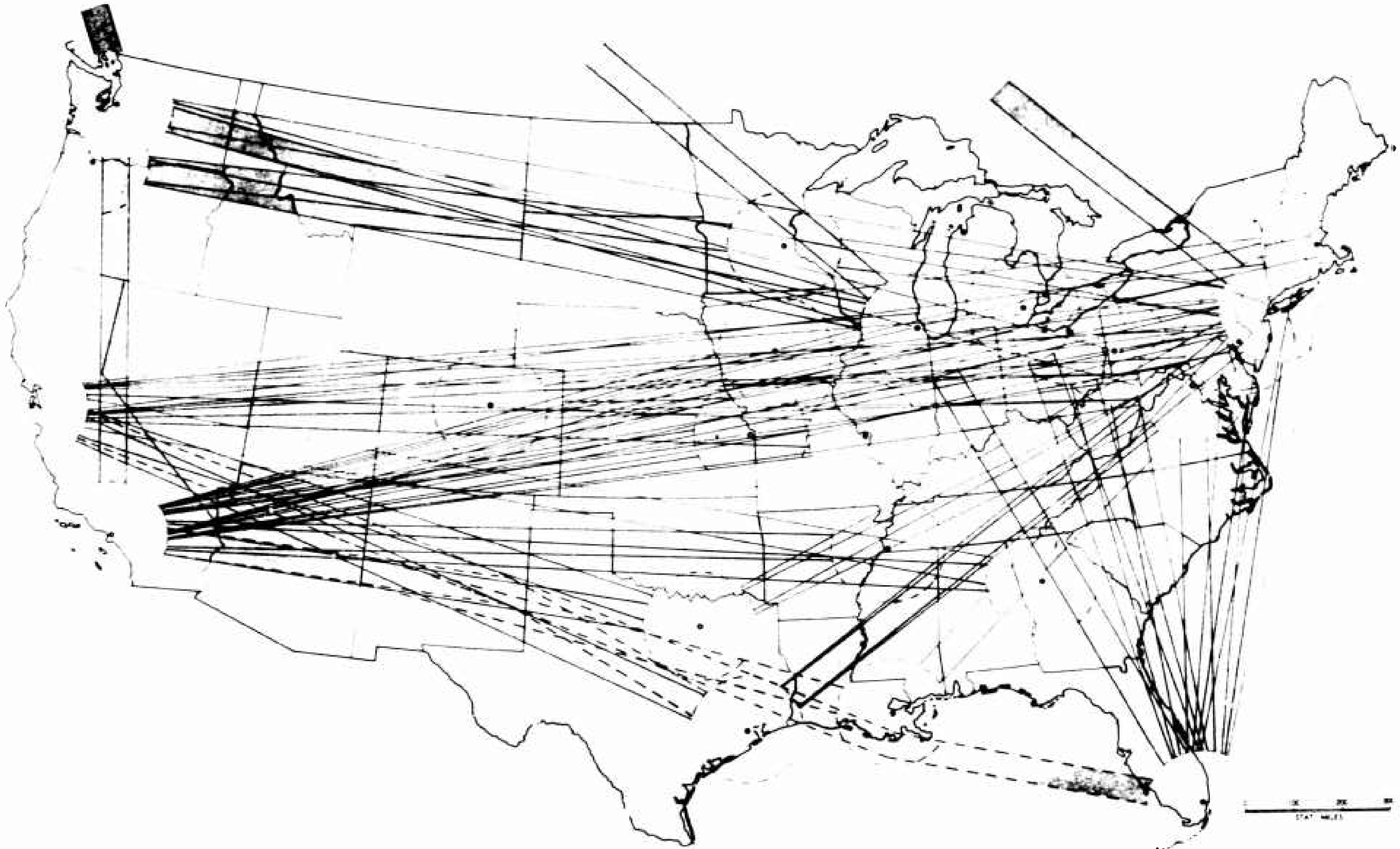


FIGURE 4-7 US Route—Configuration 3

TABLE 4-3

US ROUTE-CONFIGURATION 3

Changes from Configuration 2: Miami to L. A. moved to south of New Orleans and to north of Phoenix; Houston to L. A. moved to north of Phoenix; New Orleans to L. A. moved to north of Phoenix.

(1) City Pairs	(2) Nautical Miles, Subsonic, From 1st city	(3) Nautical Miles, Subsonic, From 2nd city	(4) Nautical Miles, Total[a]	(5) Total Cost per Trip, \$	(6) Frequency Both Ways, Flts./Day	(7) Airline Total Cost per year, $\$10^6$ (5)x(6)x365	(8) 1975 Pop. Boomed per Flt., 10^6 persons	(9) Yearly Claims Cost Person-Boom[b] Theory, $\$10^6$ 0.000231 x (8)x(6)x365
Miami-L. A.	100	100	2,030 (2,013)	9,810	2	7.16	1.994	0.35
L. A. -Houston	↓	↓	1,222 (1,198)	6,800	10	24.83	0.854	0.73
L. A. -New Orleans			1,439 (1,435)	7,590	4	11.09	1.310	0.42
							126.800[c]	

[a] Numbers in parentheses indicate total mileage for Configuration 1.

[b] Yearly claims cost, person-day theory = \$0.00165 x 126,800,000 x 365 = \$76,400,000.

[c] Total 1975 population boomed (see footnote c, Table 4-1).

FIGURE 4-8 US Route—Configuration 4

[redacted]

TABLE 4-4

US ROUTE-CONFIGURATION 4

Changes from Configuration 3: San Fran. to Atlanta moved to north of Memphis; N. Y. C. to Dallas moved to northwest of Memphis; Wash. D. C. to Dallas moved to northwest of Memphis.

(1) City Pairs	(2) Nautical Miles, Subsonic, From 1st city	(3) Nautical Miles, Subsonic, From 2nd city	(4) Nautical Miles, Total[a]	(5) Total Cost per Trip, $	(6) Frequency Both Ways, Flts./Day	(7) Airline Total Cost per year, $10^6 (5)x(6)x365	(8) 1975 Pop. Boomed per Flt., 10^6 persons	(9) Yearly Claims Cost Person-Boom[b] Theory, $10^6 0.000231 x (8)x(6)x365
San Fran.-Atlanta	100	100	1,861 (1,830)	9,128	2	6.66	2.359	0.39
Dallas-N. Y. C.	↓	↓	1,209 (1,185)	6,779	16	39.60	6.591	8.90
Dallas-Wash. D. C.	↓	↓	1,017 (1,996)	6,068	10	22.15	3.110	2.62
							124.700[c]	

[a] Numbers in parentheses indicate total mileage for Configuration 1.

[b] Yearly claims cost, person-day theory = \$0.00165 x 124,700,000 x 365 = \$75,000,000.

[c] Total 1975 population boomed (see footnote c, Table 4-1).

[redacted]

[redacted]

FIGURE 4-9 US Route—Configuration 5

[redacted]

[redacted]

TABLE 4-5

US ROUTE-CONFIGURATION 5

Changes from Configuration 4: Boston to L. A. moved north to avoid Chicago, Detroit & Denver; Boston to San Fran. moved north to avoid Chicago & Detroit, south to avoid Salt Lake; N. Y. C. to Minneapolis moved north to avoid Detroit.

(1) City Pairs	(2) Nautical Miles, Subsonic, From 1st city	(3) Nautical Miles, Subsonic, From 2nd city	(4) Nautical Miles, Total[a]	(5) Total Cost per Trip, \$	(6) Frequency Both Ways, Flts./Day	(7) Airline Total Cost per year, $\$10^6$ (5)x(6)x365	(8) 1975 Pop. Boomed per Flt., 10^6 persons	(9) Yearly Claims Cost Person-Boom[b] Theory, $\$10^6$ 0.000231 x (8)x(6)x365
L. A.-Boston	100	100	2,304 (2,243)	10,871	4	15.89	3.747	1.27
San Fran.-Boston	↓	↓	2,348 (2,322)	11,095	2	8.10	3.735	0.62
Minneapolis-N. Y. C.	↓	↓	891 (883)	5,706	2	4.17	2.913	0.51
							114.600[c]	

[a] Numbers in parentheses indicate total mileage for Configuration 1.

[b] Yearly claims cost, person-day theory = \$0.00165 x 114,600,000 x 365 = \$69,000,000.

[c] Total 1975 population boomed (see footnote c, Table 4-1).

[redacted]

FIGURE 4-10 US Route—Configuration 6

TABLE 4-6

US ROUTE-CONFIGURATION 6

Changes from Configuration 5: N. Y. C. to New Orleans moved to north of Atlanta.

(1) City Pairs	(2) Nautical Miles, Subsonic, From 1st city	(3) Nautical Miles, Subsonic, From 2nd city	(4) Nautical Miles, Total[a]	(5) Total Cost per Trip, $	(6) Frequency Both Ways, Flts./Day	(7) Airline Total Cost per year, $$10^6$ (5)x(6)x365	(8) 1975 Pop. Boomed per Flt., 10^6 persons	(9) Yearly Claims Cost Person-Boom[b] Theory, $$10^6$ 0.000231 x (8)x(6)x365
New Orleans-N. Y. C.	100	100	1,035 (1,016)	6,162	10	22.50	8.219	6.94
							114.310[c]	

[a]Number in parentheses indicates total mileage for Configuration 1.

[b]Yearly claims cost, person-day theory = \$0.00165 x 114,310,000 x 365 = \$68,900,000.

[c]Total 1975 population boomed (see footnote c, Table 4-1).

[redacted]

JRE 4-11 US Route—Configuration 7

[redacted]

[redacted]

TABLE 4-7

US ROUTE-CONFIGURATION 7

Changes from Configuration 6: N. Y. C. to Houston subsonic south of Wash. D. C. to avoid urban areas between N. Y. C. & Wash. D. C.; N. Y. C. to New Orleans subsonic south of Wash. D. C. to avoid urban areas between N. Y. C. & Wash. D. C.

(1) City Pairs	(2) Nautical Miles, Subsonic, From 1st city	(3) Nautical Miles, Subsonic, From 2nd city	(4) Nautical Miles, Total[a]	(5) Total Cost per Trip, $	(6) Frequency Both Ways, Flts./Day	(7) Airline Total Cost per year, $$10^6$ (5)x(6)x365	(8) 1975 Pop. Boomed per Flt., 10^6 persons	(9) Yearly Claims Cost Person-Boom[b] Theory, $$10^6$ 0.000231 x (8)x(6)x365
N. Y. C. -Houston	191	100	1,230 (1,230)	7,239	4	10.58	3.833	1.31
N. Y. C. -New Orleans	↓	↓	1,035 (1,116)	6,505	10	23.74	2.550	2.16
							111.244[c]	

[a] Numbers in parentheses indicate total mileage for Configuration 1.

[b] Yearly claims cost, person-day theory = $0.00165 x 111,244,000 x 365 = $67,100,000.

[c] Total 1975 population boomed (see footnote c, Table 4-1).

[redacted]

[redacted]

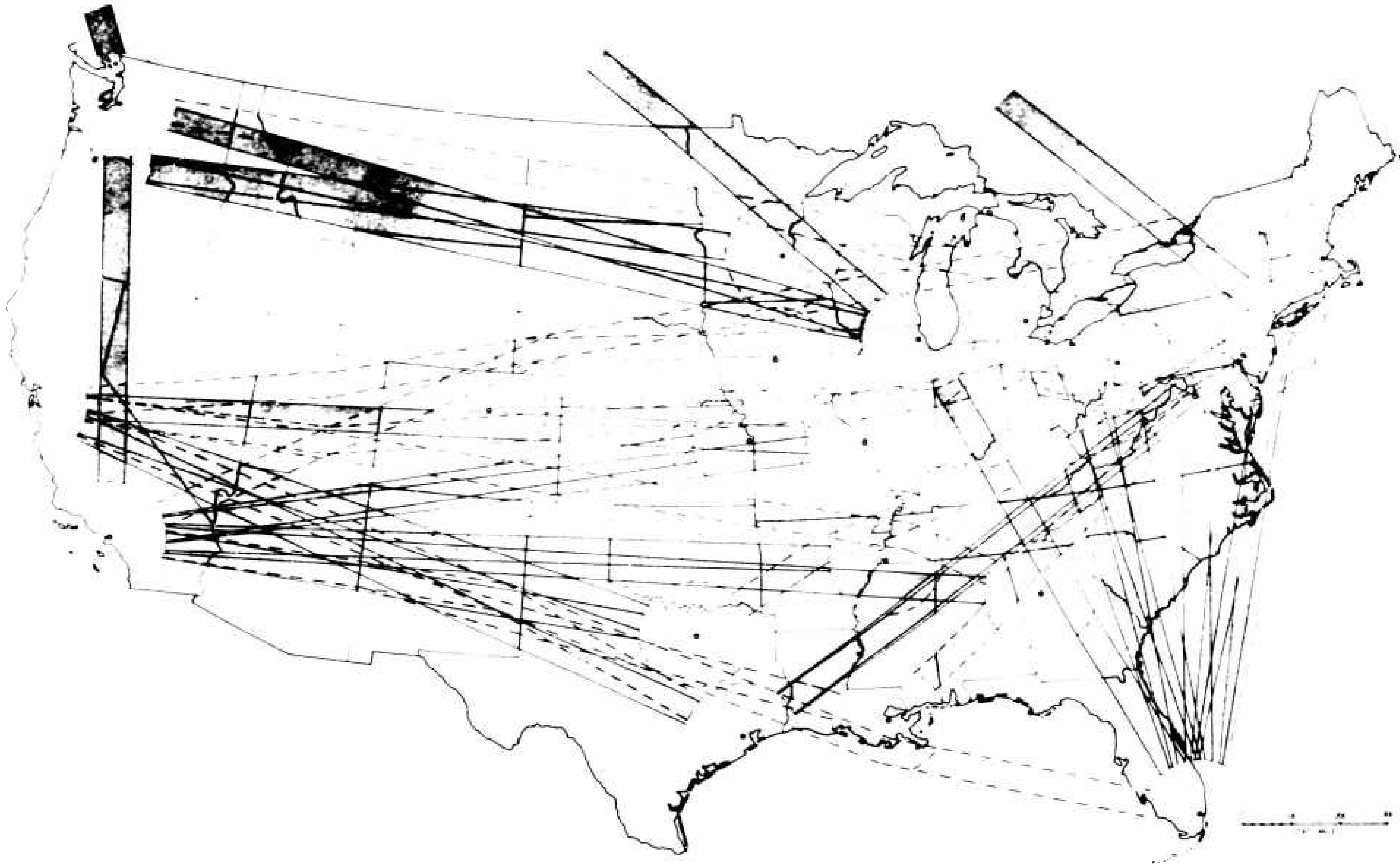


FIGURE 4-12 US Route—Configuration 8

[redacted]

[redacted]

TABLE 4-8

US ROUTE-CONFIGURATION 8

Changes from Configuration 7: N.Y.C. to San Fran. moved south to avoid Pittsburgh, Cleveland, Chicago & Denver; N.Y.C. to L.A. moved south to avoid Pittsburgh; N.Y.C. to Seattle moved north of Minneapolis; N.Y.C. to Kansas City moved south to avoid Pittsburgh; Wash. D.C. to Seattle moved north to avoid Pittsburgh, Cleveland, Chicago, Detroit & Minneapolis; Wash. D.C. to San Fran. channeled into N.Y.C. to San Fran. route, south of Denver; Wash. D.C. to L.A. channeled into N.Y.C. to L.A. route, and moved north of St. Louis; Chicago to L.A. moved north to avoid Des Moines, and north of Denver; Chicago to San Fran. moved north to avoid Des Moines, south to avoid Salt Lake; L.A. to Cleveland moved south to avoid Chicago; L.A. to Detroit moved south to avoid Chicago; L.A. to Des Moines moved south to avoid Denver; L.A. to Phila. moved north of Kansas City, and south of Pittsburgh; San Fran. to Phila. moved south of Denver, south of Pittsburgh; Denver to Wash. D.C. channeled into Wash. D.C. to San Fran route; Denver to N.Y.C. channeled into N.Y.C. to L.A. route, and moved south of Cleveland & Chicago.

(1) City Pairs	(2) Nautical Miles, Subsonic, From 1st city	(3) Nautical Miles, Subsonic, From 2nd city	(4) Total[a]	(5) Total Cost per Trip, $	(6) Frequency Both Ways, Flts./Day	(7) Airline Total Cost per year, $$10^6$ (5)x(6)x365	(8) 1975 Pop. Boomed per Flt., 10^6 persons	(9) Yearly Claims Cost Person-Boom[b] Theory, $$10^6$ 0.000231 x (8)x(6)x365
N.Y.C.-San Fran.	100	100	2,274 (2,222)	10,738	26	101.90	8.133	17.83
N.Y.C.-L.A.	↓	↓	2,178 (2,126)	10,366	24	128.60	8.252	23.68
N.Y.C.-Seattle	↓	↓	2,104 (2,096)	10,059	4	14.69	3.800	1.27
Kansas City-N.Y.C.	↓	↓	970 (952)	5,958	4	8.70	7.175	2.43
Wash. D.C.-Seattle	↓	↓	2,050 (1,987)	9,862	4	14.40	3.061	1.04
Wash. D.C.-San Fran.	↓	↓	2,083 (2,078)	10,018	4	14.63	5.953	2.00
Wash. D.C.-L.A.	↓	↓	1,987 (1,967)	9,621	22	77.30	6.073	11.30
Chicago-L.A.	↓	↓	1,530 (1,496)	7,915	50	144.50	1.837	7.75
Chicago-San Fran.	↓	↓	1,591 (1,578)	8,144	32	95.05	1.753	4.74
L.A.-Cleveland	↓	↓	1,791 (1,757)	8,918	10	32.55	3.810	3.20

(cont'd.)

[redacted]

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TABLE 4-8

US ROUTE-CONFIGURATION 8—Continued

(1) City Pairs	(2) Nautical Miles, Subsonic, From 1st city	(3) Nautical Miles, Subsonic, From 2nd city	(4) Total[a]	(5) Total Cost per Trip, \$	(6) Frequency Both Ways, Flts./Day	(7) Airline Total Cost per year, $\$10^6$ (5)x(6)x365	(8) 1975 Pop. Boomed per Flt., 10^6 persons	(9) Yearly Claims Cost Person-Boom[b] Theory, $\$10^6$ 0.000231 x (8)x(6)x365
L. A.-Detroit	100	100	1,739 (1,690)	8,689	4	12.69	2.979	1.00
L. A.-Des Moines	↓	↓	1,280 (1,239)	7,016	2	5.12	0.804	0.15
L. A.-Phila.	↓	↓	2,109 (2,055)	10,112	6	22.17	6.267	3.16
San Fran.-Phila.	↓	↓	2,197 (2,158)	10,441	2	7.63	6.147	1.04
Denver-Wash. D.C.	↓	↓	1,268 (1,235)	6,990	4	10.21	5.624	1.89
Denver-N. Y. C.	↓	↓	1,457 (1,407)	7,668	6	16.80	7.803	3.93
					214	706.94	70.690[c]	66.41

[a]Numbers in parentheses indicate total mileage for Configuration 1.

[b]Yearly claims cost, person-day theory = \$0.00165 x 70,690,000 x 365 = \$42,600,000.

[c]Total 1975 population boomed (see footnote c, Table 4-1).

[redacted]

[redacted]

The cumulative route modifications through Configuration 8 resulted in an increase in airplane costs of approximately \$13 million or 1 percent more than the all-great circle configuration (Table 4-9). The yearly best-judgment claims costs are reduced from \$103.5 million for Configuration 1 to \$58.2 million for Configuration 8. Each of the seven modifications was "profitable;" i.e., the best-judgement claims cost was reduced by an amount greater than the increase in airplane operating costs. It should be noted that no account was taken of the possibility of "focusing" booms at bends in the flight tracks. These bends will result in higher claims in the areas where they occur, and will tend to reduce the claims cost reductions as shown in Table 4-9. Although the change in Configuration 8 was highly profitable, we believe that little more can be done in the way of further profitable modifications, and that Configuration 8 approximates a minimal combined cost of airplane operation plus claims. On Configuration 8, the routes have been modified about as much as is practical insofar as circuitous routing around relatively dense areas of population is concerned. Accordingly, the only way to significantly "uncover" the total boomed population further is to fly greater distances subsonically at the beginning or end of the supersonic cruise segment. The average trip distance for the 52 domestic city pairs is about 1500 n. mi. Accordingly, from Figure 4-5, the average additional cost per nautical mile of extra subsonic cruise is about \$4.60. From Table 4-1, the daily flight frequency is 464. Hence, the additional yearly cost if each flight flies one extra nautical mile subsonically is:

$$464 \times 365 \times 4.60 = \$779,000.$$

From Table 4-9, the yearly best-judgment claims cost for Configuration 8 is \$58,200,000. The added airplane costs would equal the total claims costs if an additional 75 n. mi. of each route were flown subsonically. Hence, it can be seen that only very minor additional segments of the route network could be flown subsonically or the added airplane costs would increase much more rapidly than the claims costs would decrease.

In Configuration 8, the common track with the maximum flight frequency is near the Illinois-Indiana border and has 120 flights per day along it. We have ignored any air traffic control problems that may result from such superimposing of flights. Such problems may limit the extent to which routes can be superimposed. However, it will probably be possible to superimpose routes at least partially. With a band of flight tracks 10 n. mi. wide, the width of the boom envelope would be 60 instead of 50 n. mi.

Assuming that no air traffic control problems are created which would require major expenditures to solve, the most practical way to reduce total claims costs is to channel flights between different city pairs into common

[redacted]

TABLE 4-9

TRADEOFFS BETWEEN AIRPLANE OPERATING COSTS AND CLAIMS COSTS FOR MODIFICATIONS TO ROUTE-CONFIGURATION

			Person-Boom		Person-Day			Best-Judgment	
Route Config.	Total Airplane Cost per Yr, $\$10^6$	Add'l. Airplane Cost per Yr, $\$10^6$	Yearly Claims Cost, $\$10^6$	Reduction in Yearly Claims Cost, $\$10^6$	Yearly Claims Cost, $\$10^6$	Reduction in Yearly Claims Cost, $\$10^6$	Average Daily Boom Frequency	Yearly Claims Cost, $\$10^6$	Reduction in Yearly Claims Cost, $\$10^6$
1	1,314.13	—	199.93	—	80.00	—	17.7	103.5	—
2	1,314.16	0.03	199.46	0.47	77.50	2.50	18.5	102.1	1.4
3	1,314.53	0.40	197.47	2.46	76.40	3.60	18.5	100.8	2.7
4	1,315.36	1.23	196.85	3.08	75.00	5.00	18.8	98.9	4.6
5	1,315.78	1.65	190.03	9.90	69.00	11.00	19.5	92.5	11.0
6	1,315.84	1.71	190.11	9.82	68.90	11.10	19.5	92.4	11.1
7	1,317.74	3.61	184.25	15.68	67.10	12.90	19.5	90.0	13.5
8	1,327.52	13.39	130.68	69.25	42.60	37.40	21.5	58.2	45.3

tracks. Accordingly, the boom frequency along these common tracks will be much higher than in the all-great circle case. Even in the all-great circle case, Northern Arizona is subjected to 166 booms per day. An area of Iowa has 84 booms per day; an area of Nebraska has 82.

As can be seen from Figure 4-2, many of the large coastal cities are not subjected to booms even in the all-great circle case. Further, the most fruitful procedure for reducing claims costs is to "uncover" large cities and move the routes into the rural areas. Accordingly, it can be seen that the population areas benefiting most from the SST service will suffer least from the boom effects and vice versa.

4.4 ANALYSIS OF FOREIGN SST ROUTES

Table 4-10 lists the 86 foreign routes considered. We have included flights between the 48 conterminous US states and Anchorage and Honolulu. Great circle tracks for these routes are depicted on Figure 4-13. The basic map used in Figure 4-13 depicts 1960 population density per square

TABLE 4-10

FOREIGN ROUTE ANALYSIS

City Pairs	Great Circle Distance, n. mi.	Daily Flight Frequency Both Ways, flts./day	1960 Pop. Boomed Great Circle, 10^6 persons	Ease of Avoiding Pop.[a]	Type of Ground Construction[a]	Overall Category[a]	Airplane Daily Route Mileage, n. mi.
San Juan-N.Y.C.	1,391	46	0	0	0	0	64,000
Manila-Tokyo	1,616	11					17,780
Honolulu-Nandi	2,755	3					8,260
Nandi-Sydney	1,710	3					5,130
Honolulu-Tokyo	3,342	5					16,720
San Fran.-Honolulu	2,081	7					14,560
L.A.-Honolulu	2,217	10					22,170
Portland-Honolulu	2,260	2					4,520
						Total for overall category 0:	153,160
Caracas-Azores	2,753	1	0.43	1	1	1	2,753
Anchorage-Copenhagen	3,750	1	0.44	2	3		3,750
Anchorage-Tokyo	3,008	4	0.28	1	3		12,030
Beirut-Bombay	2,178	3	0.75	1	1		6,530
Caracas-Lima	1,488	2	0.37	3	1		2,980
Caracas-Miami	1,183	2	0.39	1	2		2,370
Caracas-N.Y.C.	1,837	5	0.14	1	2		9,190
Copenhagen-N.Y.C.	3,336	3	5.02	1	3		10,000
Dakar-Rio	2,735	1	2.73	1	2		2,735
Houston-Mexico City	648	2	0.50	3	2		1,296
Johannesburg-Accra	2,521	1	0.47	3	1		2,521
Cairo-Nairobi	1,913	1	8.50	1	1		1,913
Lima-Mexico City	2,298	4	0.65	3	2		9,200
Madrid-Rome	733	2	6.08	1	2		1,465
Mexico City-Miami	1,109	8	0.15	2	2		8,880
Mexico City-New Orleans	790	2	0.29	2	2		1,580
Miami-San Juan	907	10	0.29	1	2		9,070
New Orleans-San Juan	1,492	1	0.40	1	3		1,492
N.Y.C.-Shannon	2,668	2	4.05	1	3		5,340
Sydney-Darwin	1,702	2	0.17	3	1		3,404
Seattle-Anchorage	1,255	8	0.15	1	3		10,040
Buenos Aires-Lima	1,694	6	0.96	3	2		10,180
Lima-Miami	2,281	1	0.99	3	2		2,281
Boston-Shannon	2,508	3	0.58	1	3		7,520
Cairo-Bombay	2,345	3	0.29	2	1		7,040

(cont'd.)

[redacted]

TABLE 4-10

FOREIGN ROUTE ANALYSIS—Continued

City Pairs	Great Circle Distance, n. mi.	Daily Flight Frequency Both Ways, flts./day	1960 Pop. Boomed Great Circle, 10^6 persons	Ease of Avoiding Pop.[a]	Type of Ground Construction[a]	Overall Category[a]	Airplane Daily Route Mileage, n. mi.
Caracas-Rio	2,450	3	0.74	1	1	1	7,350
Lima-Rio	2,031	1	1.19	1	2		2,031
San Juan-Rio	2,819	1	0.87	1	1		2,819
Chicago-Anchorage	2,478	2	0.91	3	3		4,950
Nairobi-Rome	2,914	2	0.96	2	1		5,820
						Total for overall category 1	158,530
Amsterdam-N.Y.C.	3,158	6	12.58	2	3	2	18,940
Beirut-Nairobi	2,127	1	1.58	3	1		2,127
Baghdad-Bombay	1,750	12	1.31	2	1		21,000
Bangkok-Bombay	1,626	18	9.05	3	1		29,250
Bangkok-Manila	1,187	18	2.34	3	1		21,350
Beirut-Rome	1,182	10	4.75	2	2		11,820
Brussels-Montreal	2,997	1	6.20	2	3		2,997
Brussels-N.Y.C.	3,176	3	13.79	2	3		9,520
Buenos Aires-Rio	1,076	7	1.67	2	2		7,540
Cairo-Rome	1,159	7	1.41	2	2		8,110
Azores-Madrid	1,031	1	2.09	2	2		1,031
Dakar-Madrid	1,707	2	1.36	3	2		3,410
Frankfurt-N.Y.C.	3,340	8	19.09	2	2		26,750
Zurich-N.Y.C.	3,405	11	9.34	2	2		37,400
Madrid-N.Y.C.	3,110	8	7.57	2	2		24,900
London-Montreal	2,815	4	3.82	2	3		11,270
L.A.-Mexico City	1,348	6	2.29	2	2		8,090
Montreal-Amsterdam	2,971	2	5.55	2	3		5,940
Montreal-Paris	2,978	4	2.80	2	3		11,910
Montreal-Zurich	3,236	1	5.87	2	3		3,236
N.Y.C.-Paris	3,148	16	6.30	2	3		50,400
Boston-London	2,828	4	5.66	2	3		11,320
Boston-Paris	2,987	1	2.08	2	3		2,987
London-N.Y.C.	2,989	27	9.42	2	3		80,600
London-Phila.	3,070	1	12.10	2	3		3,070
Paris-Phila.	3,229	1	9.88	2	3		3,229
Darwin-Bangkok	2,394	2	2.31	2	1		4,790
Nairobi-Johannesburg	1,571	1	2.06	3	1		1,571
						Total for overall category 2:	434,378

[redacted]

[redacted]

TABLE 4-10

FOREIGN ROUTE ANALYSIS—Continued

City Pairs	Great Circle Distance, n. mi.	Daily Flight Frequency Both Ways, flts./day	1960 Pop. B[illegible]ed Great Circle, 10^6 persons	Ease of Avoiding Pop.[a]	Type of Ground Construction[a]	Overall Category[a]	Airplane Daily Route Mileage, n. mi.
Accra-London	2,752	1	9.22	3	2	3	2,752
Beirut-Paris	1,725	5	13.69	3	2		8,630
Beirut-Frankfurt	1,531	4	7.59	3	2		6,130
Beirut-Zurich	1,462	4	9.06	3	2		5,860
Beirut-London	1,878	3	12.57	3	3		5,630
San Juan-Montreal	1,693	1	4.47	3	3		1,693
Cairo-Frankfurt	1,576	2	4.70	3	2		3,150
Cairo-Zurich	1,480	3	7.32	3	2		4,440
Cairo-London	1,905	1	13.46	3	2		1,905
Chicago-London	3,426	6	6.94	3	3		20,560
Chicago-Mexico City	1,461	4	3.11	3	3		5,850
Chicago-San Juan	1,787	1	3.32	3	3		1,787
Copenhagen-Rome	829	2	9.53	3	2		1,658
Dakar-Paris	2,276	1	4.77	3	2		2,276
Frankfurt-Madrid	768	1	4.69	3	2		768
London-Rome	789	22	14.77	3	2		17,370
Mexico City-N.Y.C.	1,818	5	3.69	3	3		9,090
Mexico City-Montreal	2,004	1	7.08	3	3		2,004
Rome-Baghdad	1,584	1	4.62	3	2		1,584
N.Y.C.-Anchorage	2,932	2	1.77	3	3		5,860

Total for overall category 3: 108,997

[a] 0 = no problem;
1 = minimal problem;
2 = intermediate problem;
3 = maximal problem.

[redacted]

[redacted]

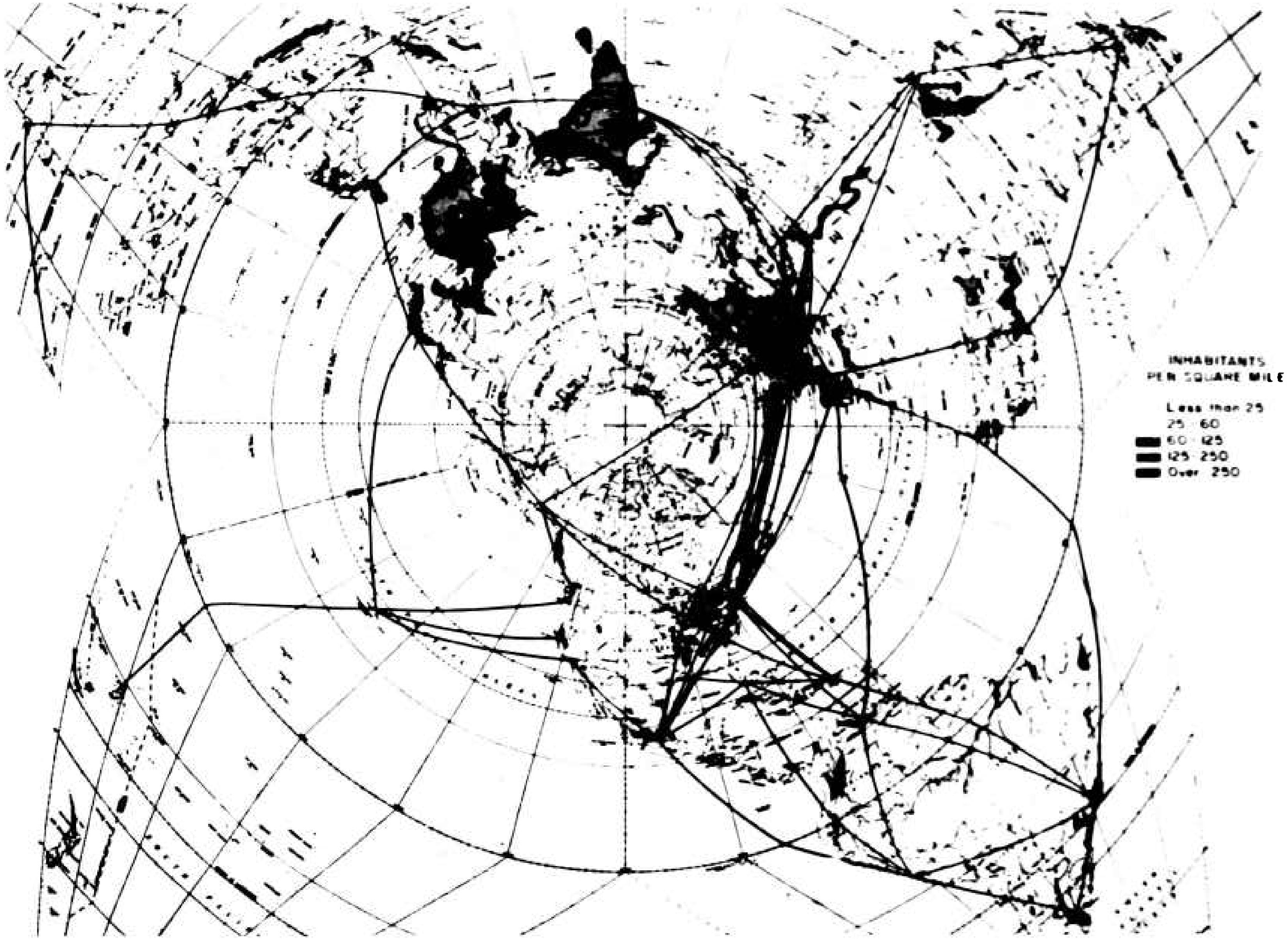

FIGURE 4-13 International Routes (Basic map by Rand-McNally; copyright license 64-S-122)

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statute mile. The 1960 population boomed on each route has been calculated from this map and entered in Table 4-10. We have not projected these figures to 1975 as was done in the case of the US routes.

The highest population density on Figure 4-13 is denoted as "over 250 per sq mi." Actual population densities for several areas of the world which are largely in the "over 250" density category are:

	Area, sq st mi	1960 Population	1960 Density
Rhode Island	1.058	859.000	810
New Jersey	7,522	6.067.000	810
Connecticut	4,899	2.535,000	520
Massachusetts	7,867	5,149.000	650
Belgium	11,779	9.200,000	780
Netherlands	13,025	11,500,000	880
E. Pakistan	54.501	48,000,000	880
Java & Madura	51,032	57,000,000	1120
Honshu Is. (Japan)	88.952	72,000,000	810

The population density of metropolitan areas is of the order of 10,000 per sq. mi. In our route population counts, we calculated the population in the "over 250" density areas by assuming an average density of 800 per sq mi for these areas. This method is not as exact as that used for the US where we counted population by county. However, it provides a good picture of the relative populations boomed on the various routes.

Several of the North Atlantic routes lie virtually on top of each other. As a result, although there are twenty North Atlantic routes included in Table 4-10, there are only ten tracks shown on Figure 4-13 in the mid-North Atlantic. These ten tracks cover all 20 routes as follows:

(1)	N. Y. C. - London	Boston - Shannon
	Boston - London	N. Y. C.- Shannon
	N. Y. C. - Brussels	London - Philadelphia
(2)	N. Y. C. - Zurich	Boston - Paris
	N. Y. C. - Paris	Philadelphia - Paris
(3)	Montreal - Brussels	Montreal - London
(4)	Montreal - Zurich	Montreal - Paris
(5)	Copenhagen - N. Y. C.	
(6)	Amsterdam - N. Y. C.	
(7)	Frankfurt - N. Y. C.	
(8)	Madrid - N. Y. C.	
(9)	Montreal - Amsterdam	
(10)	Chicago - London	

We have not attempted to quantify claims costs for the foreign routes since we do not feel that US claims data are

[redacted]

applicable to foreign routes. Since the great majority of claims involves alleged damage to buildings, we would expect that claims costs would be a function of the susceptibility of buildings to damage by the boom, and to other damage that could be mistakenly attributed to the sonic boom. Since most of the damage claims involve cracking in brittle surface materials (glass, plaster, tile), we would expect the level of claims cost to vary directly with the level of sophistication of construction. We would characterize the construction of the US, Canada, and Europe as sophisticated. The economically undeveloped countries, particularly in the tropics, would be characterized by unsophisticated indigenous construction. This type of construction has little or no brittle surface materials. (See Section C, Structural Responses to Sonic Boom, for a more complete discussion of this subject.)

We have grouped the 86 foreign routes into four categories:

Category 0 No boom problem
1 Minimal boom problem
2 Intermediate boom problem
3 Maximal boom problem

In determining a route category, three factors were considered: (1) number of people boomed by great circle route; (2) ease of avoiding population by circuitous routing or extra subsonic cruise; (3) susceptibility of ground construction to boom damage (or to other damage which might be attributed to boom).

Table 4-10 shows the routes by the four categories. The routes were categorized by rating each route by each of the above three factors and then determining the overall category by means of Table 4-11. The route frequency and great circle distance are included in Table 4-10 to indicate the relative economic importance of the routes. The flight frequencies are in general representative of present non-stop jet flight frequencies over these or similar routes[4]. The distribution of daily airplane mileage among the four categories is as follows:

Category	Airplane Daily Route Mileage	Percent of Total Mileage
0	153,160	18
1	158,530	19
2	424,558	50
3	108,997	13
	845,245	100

The categorization of ease of avoiding population was quite subjective. Routes between US East Coast cities and London and Paris were categorized as 2 because of the problem of missing the densely populated areas of Western England and France. However, this problem could be met

[redacted]

TABLE 4-11

ROUTE CATEGORIZATION METHOD[a]

No. of People Boomed, 10^6 persons	Ease of Avoiding Population	Ground Construction Susceptibility to Boom Damage	Overall Category
0			0
0 - 1.30	1	1, 2, 3	1
	2	1, 2, 3	
	3	1, 2, 3	
1.30 - 4.60	1	1, 2, 3	
	2	1, 2, 3	2
	3	1, 2, 3	3
4.60	1	1, 2, 3	1
	2	1, 2, 3	2
	3	1, 2, 3	3

[a] 0 = no problem;
1 = minimal problem;
2 = intermediate problem;
3 = maximal problem.

by flying up the English Channel and then decelerating to subsonic speeds before heading for London and Paris. These routes seem to be on the border between categories 1 and 2. Because of the high airplane mileages generated on these routes, a transfer of these routes to category 1 from category 2 would have a major effect on the percent breakdown by category shown in the paragraph above.

The routes of category 0 should incur no claims costs; those of category 1 should incur only very minor claims costs if the airplane operation is compromised slightly on those routes where most of the population boomed can be easily avoided. Routes of the last two categories will involve significant claims costs. Further testing (ideally Oklahoma City type tests in foreign countries) and analyses are needed to estimate the magnitude of these costs.

4.5 REFERENCES

1. Official Airline Guide. September 15, 1964.

2. US Department of Commerce, Bureau of the Census. 1960 Census of Population, Vol. 1, "Characteristics of the Population."

3. Cornell Aeronautical Laboratory, Analysis of Population Size in the Sonic Effects Zone Along Likely SST Routes, SST Memorandum No. 507, June 1964.

4. Official Airline Guide, International Edition, September 1964.

5

STRUCTURAL RESPONSE TO SONIC BOOM

5

STRUCTURAL RESPONSE TO SONIC BOOM

Section 3 indicates that most sonic boom damage claims involve damage to buildings. The purposes of this section are

(1) to examine the structural response of buildings to sonic booms as an aid in interpreting past claims data,

(2) to determine whether or not the differences between the SST and the airplanes used in previous tests will result in significantly different sonic boom effects on buildings,

(3) to estimate the relative susceptibility to boom damage of the various types of buildings which would be overflown during foreign operations.

5.1 SHOCK WAVE EFFECTS ON BUILDINGS

The possibility of serious boom damage to buildings has received wide publicity after episodes like those at Cedar City, Utah; Panama City, Florida; and Ottawa, Canada. These are briefly described in Appendix A. Unfortunately, the results of the limited research so far undertaken do not yet permit an adequate definition of the extent and characteristics of boom damage and the overpressure thresholds at which damage occurs.

The Oklahoma City test program added considerably to the understanding of structural responses and damage effects, although significant gaps remain. Nine wood-framed residential buildings within the boom path and two outside the boomed area (for control purposes) were inspected daily for effects during all or part of the six-month, 1253-boom test period. Several of these were extensively instrumented to measure the linear strains (changes in length due to compression or tension) in framing members like studs and rafters, the accelerations imposed on various parts of the buildings by the shock wave, the displacements and deflections of various structural elements, as well as humidity, temperature; and other data. Fuller details of the structural response test plan are contained in Appendix B.

The overpressures and other dimensions of the 1253 sonic booms have been analyzed in this report (see Appendix B) and by NASA.[42*] These analyses indicate that the overpressures experienced were on the whole markedly lower than had been programmed in an effort to simulate

*Superscript numbers indicate items in the numbered bibliography at the end of this section.

expected SST overpressures. Nevertheless, a suitable distribution of flights in the SST operating range was obtained.

A word of caution is necessary about the accuracy of the overpressure measurements made in this test. Evaluations on several occasions of the microphones used at Oklahoma City indicate that the overpressure readings on seven carefully calibrated microphones placed within a one-foot-square area may produce readings that differ by as much as 30 percent (see Appendix B). It is also known that overpressure measurements at fairly closely spaced points may vary considerably more than this, apparently due to the effect of atmospheric turbulence at the lower altitudes. In one test, overpressure values of 0.73 and 3.55 psf were recorded at points 100 feet apart under the flight track, where a nominal overpressure of 1.5 psf was expected.[15]

These phenomena cast some doubt on the actual overpressure experienced by some part of a structure 50 feet away from the recording microphone.

This study will consider separately the damage effects first on the "primary structure" (the load-bearing system) of a building, and second on certain remaining components which appear more susceptible to sonic boom damage.

The "primary structure" of a masonry house consists of its foundations, its load-bearing walls, and the wood framing or other supporting systems of floor, interior wall, roof, and similar components. In the common frame house, which is generally wood-framed except in minor instances where steel or aluminum has been used, the "primary structure" substitutes wood-framed exterior wall panels for the masonry walls of the masonry house. The exterior of the frame house may have a veneer of brick or stone masonry.

Excluded from the term "primary structure" are the doors, windows, exterior siding or veneers, interior wall, floor and ceiling surfaces, and the various utility systems. Some of these, like exterior siding and interior surfaces, may in fact add to the structural strength of the house, but this is not their primary purpose.

From the structural response measurements made at House 1 during the 1253 test flights, those for 329 flights were made available for this study. Their distribution by type of aircraft and flight track is shown in Figure B-9. Apparently these were selected by FAA Oklahoma City program personnel for their own analyses as well. This was done, it appears, in order to limit the scope of the task through use of representative samples and especially significant flights. The selection appeared to be suitable. All strain and acceleration measurements in House 5 (183 flights during July) were provided.

[redacted]

5.1.1 Effects on Primary Structures

Each sonic boom overpressure uniformly loaded the surface of each roof, wall, or ceiling panel. The loading was then distributed to each of the rafters, studs, or joists in the panels from the associated part of the panel surface. The stresses induced in the rafter, stud, or joist would then be a function, not only of the load each received, but also of the material, its cross section, and its beam span.

For House 1 the peak strains recorded were 54.05 (questionable reading), 47.43, and 35.14 micro-in./in. If the modulus of elasticity for wood such as this Douglas fir framing lumber is taken as 1.6×10^6 psi, the stress values corresponding to these strains are 86.5, 76.0, and 56.2 psi, respectively. As Table 5-1 indicates, the maximum strains (and stresses) induced in House 5 were somewhat lower than those in House 1. Thus only two stress values (86.5 and 76.0 psi) out of over 3200 examined in this study exceeded 60 psi. These values are small relative to the 1100 psi allowable for such material.

The indicated stress values are, of course, increments above the pre-sonic boom dead load (structural materials) and live loads (people, furniture, wind, snow, etc.). These existing loads may of course stress the member to near the allowable stress, or in extraordinary circumstances beyond it. Nevertheless, the small additional stresses induced by the sonic boom shock wave alone would not be significant and would not damage the members of wood structural framing unless the preloading condition markedly exceeded the allowable loading. The structural members are capable of accepting brief impact loadings like those imposed by winds, earthquakes, or the sonic boom for a total load up to 1-1/3 times the allowable stress.

The interested reader can examine the characteristics of the strains induced under varying conditions in various members of a brick veneer frame rambler by studying the tables in Appendix C.*

From these tables it is evident that:

(1) surfaces on the side or sides of a building more nearly facing the incident shock wave receive greater loadings than other surfaces; and

(2) as the vertical angle of incidence of the pressure wave varies (due mainly to varying aircraft speeds) causing the wave to strike a surface more nearly "flat on" the resulting stresses increase.

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* In these tables and elsewhere in this report specific flights at Oklahoma City are identified by a two-part number as, for example, 4/748. The first part represents the number of the flight made on a given day. The second is the serial number of the flight from the first to the last of the 1253 flights. This report uses serial numbers assigned by the FAA. Those used in the NASA report on its participation in the test program generally differ by one number. Since the prefix numbers for each day agree, the two parts of the number permit the reader to identify the same test flight in the two reports.

[redacted]

TABLE 5-1

BOOM-INDUCED STRAINS AT HOUSE 5. JULY 11 to 25. INCL. (120 Flights)[a]

Gauge No.	Gauge Location	Strains, 10^{-6} in/in Average	Strains, 10^{-6} in/in Two High Readings	Δp,[b] psf	Frequency, cps	Duration of N-Wave, sec
1	Center of ceiling, living room at NW corner of house, first story. On plaster parallel to ceiling joists (floor joists of room above)	1.922	6.72 5.63	1.07 0.70	33.3	0.03
2	Center of ceiling, bedroom at NW corner of house, second story. On plaster parallel to ceiling joists	5.27	10.00 9.55	1.07 1.70	16.7	0.06
3	Center of interior side of exterior wall, west side of bedroom at NW corner of house, second story. On stud edge parallel to stud.	6.937	14.03 13.03	0.92 1.19	16.7	0.06
4	Center of interior wall, east side of bedroom at NW corner of house, second story. On stud edge parallel to stud	1.889	6.15 5.29	0.36 1.08	16	0.063
5	West slope of roof (approximately centered). On rafter edge parallel to rafter	3.858	7.44 7.20	1.90 1.70	25	0.04
6	North slope of roof (approximately centered). On rafter edge parallel to rafter (long rafter with brace removed)	22.769	35.91 34.44	1.70 2.72	5.9	0.17

a. All flights F-101 except 6 F-106 flights.

b. Corresponding to the two high strain readings. Δp range for all 120 flights: maximum, 2.99 psf; minimum, .036 psf; average, 1.16 psf.

[redacted]

The relations between the strains (stresses) induced and the corresponding overpressure and impulse measurements were examined in Appendix D. For a uniformly loaded beam such as a roof rafter, the strain would be a linear function of the overpressure loading in the form $y = bx$. For all the data points available, three functions have been computed by statistical regression, one each for the F-104, F-101, and B-58 aircraft. The near coincidence of the three lines indicates that the strain/stress responses at a given overpressure loading do not depend on the type of aircraft causing the sonic boom.

The strain-impulse relation approximates a linear function of the same form. However the lines regressed for each aircraft to quantify the relation show these to be separate and distinct lines. Thus the strain-impulse function involves a dependency on the type of aircraft which produced the boom.

A comparison was made of the stress experience in flights at the same nominal (calculated) overpressure level, but with measured overpressures which indicated varying degrees of "spike-peaking". "Spike-peak" is the term used for peaked pressure waves like the first waveform in Figure 5-1. Apparently the result of meteorological turbulence and anomalies at lower altitudes, such peaks attain pressures up to three times the nominal pressure.

Table C-6 in Appendix C shows the strains for three groups of flights, selected for overpressure values (at House No. 1) of about 1.80, 2.20, and 2.65 psf, respectively, but with all their nominal overpressure values near 1.80 psf. Only a limited sampling of flights which fit this pattern was available. Particularly if the unexplainably high 47.43 strain value (flight 6/1005) is disregarded, the strain values for the 2.20 and 2.65 psf groups are markedly lower than the data points for similar overpressures without "spike-peaking" (see data points of Figure D-1 in Appendix D.)

The last group of data in the same table compares strains from "spike peak" overpressures approximating the 1.80 psf value produced in flights whose nominal overpressure value was markedly lower (1.23 and 1.31 psf). The strains were generally lower than those produced by the first subgroup of Table C-6 whose actual and nominal overpressures were 1.80. The same phenomenon is noted in the data in Table C-7 of Appendix C.

The foregoing analyses indicate that "spike-peak" overpressures cause some of the dispersion of points shown in the plot of strains vs overpressures (Figure D-1). When "spike-peak" overpressures exceed the nominal value by some undetermined factor (apparently between 0.5 and 1.0) the strain may not continue to increase in the same relation, if at all. This phenomenon warrants further investigation because of concern over higher response levels

[redacted]

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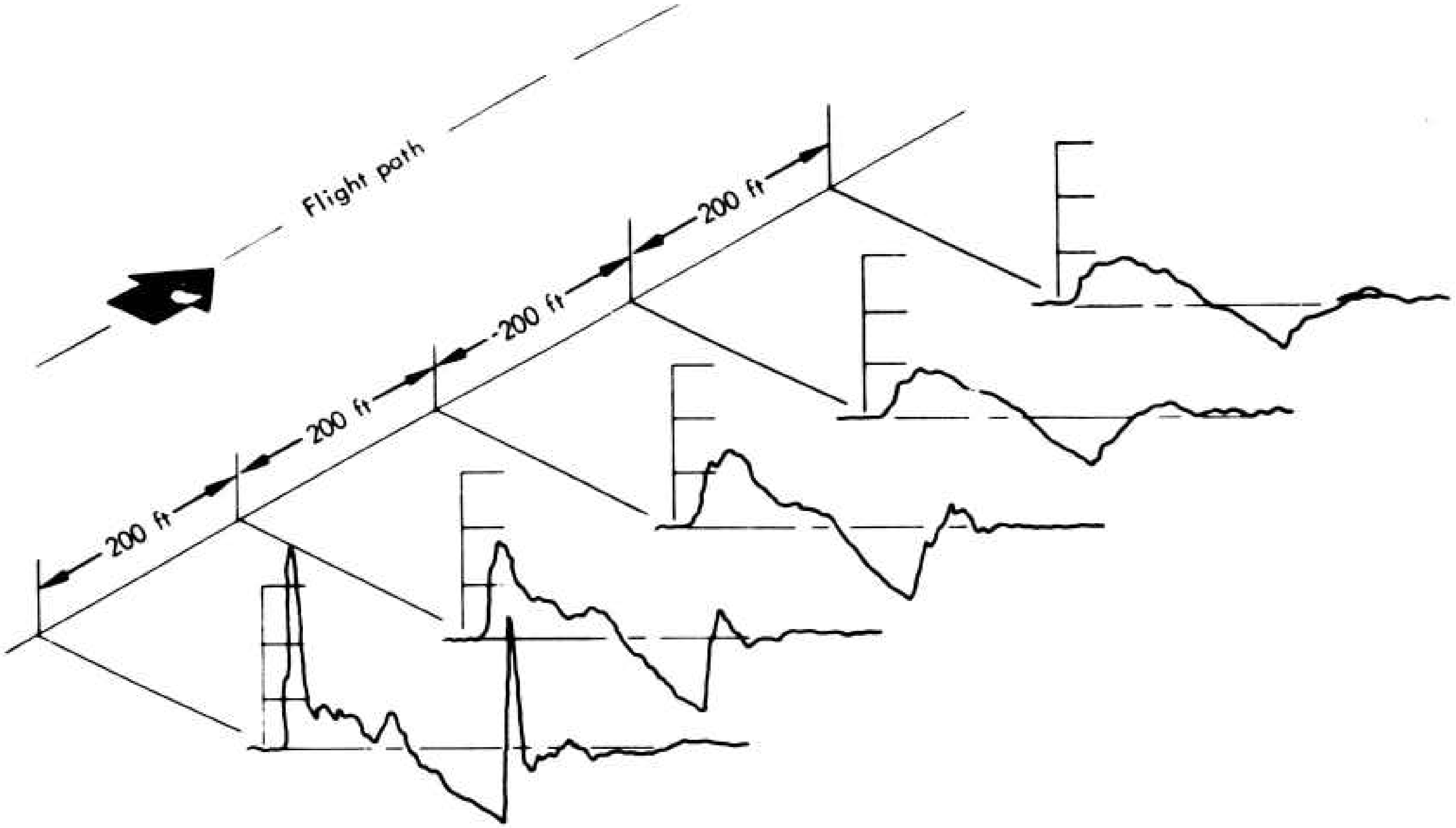

FIGURE 5-1 "Spike-Peak" and Other Waveform Variations

[redacted]

from the high-spike-peak overpressures which can result from meteorological distortion of nominal sonic booms of about 2.0 psf.

5.1.2 Effects on Plaster and Plaster-Board Surfaces

In nonresidential buildings, the use of acoustical tile, hung ceilings, and other materials and techniques have virtually eliminated any problem of plaster cracking. However the problem will continue in residential structures so long as present construction methods and standards continue.

A major cause of plaster cracking is deflection of plastered ceiling assemblies. For years engineering manuals and other sources have been perpetuating the 1/360 rule, that cracking will not occur if the design load does not cause a deflection of more than 1/360 of the span length. Investigations have shown that deflections of only 1/4 to 1/3 that "allowable" under the 1/360 formula will produce consistent cracking.[70] Nevertheless the rule continues to be widely applied.

The shearing forces induced in a wall from the force exerted by other walls normal to the first, may result in cracking (see Figure A-2 of Appendix A). Although deflection and shear are the principal modes for boom-induced plaster damage, there are numerous other causes of plaster cracks.

In considering the sonic boom as a causative, it should be noted that deflections of 0.0135 and 0.040 in. were measured in a ceiling joist in House 1. The greater deflection measured (0.040 in.) for a 2 by 6 in. ceiling roof joist in House 1 (span 23 ft. 4 in.) represents a very small fraction of the 1/360 value (0.78 in.). An entirely different situation existed in House 5, for which Table 5-2 indicates some deflections measured. Second-story ceiling joists are only 2 by 4 in. with no live load apparently intended. The 1/360 rule suggests an allowable deflection of 0.453 in. in the 163-in. span. Whereas the ceiling deflection of the first-story ceiling, with 2 by 10 in. ceiling joists, averaged 0.076 in. with maxima of 0.16 and 0.17 in., the values for the second-story ceiling averaged 0.239 in. with maxima of 0.36 and 0.40 in. Even at the first-story ceiling, the maximum values were approximately one-third the 1/360 deflection. In the Armour Research Foundation tests, cracking occurred for such values. For the second-story ceiling of House 5, the deflections measured were even greater: 79.5 and 88.4 percent of the "rule-of-thumb" figure.

Cracks caused by excess deflection do not necessarily remain visible, but may open and then close when the loading is removed. Accordingly, cracks in addition to those now visible may have been caused by excessive deflection. When a plaster ceiling fails from excessive deflection, the

[redacted]

TABLE 5-2

BOOM-INDUCED DISPLACEMENTS AT HOUSE 5, JULY 11 TO 25. (120 Flights) [a]

Gauge No.	Gauge Location	Average Reading, in.	Two High Readings, in.	Δp, psf [b]
1	Center of ceiling, living room at NW corner of house, first story. Mounted for vertical pickup	0.076	0.17 0.16	1.29 1.52
2	Center of ceiling, bedroom at NW corner of house, second story. Mounted for vertical pickup	0.239	0.40 0.36	1.66 1.29
3	Upper NW corner, bedroom at NW corner of house, second story. Mounted for east-west pickup	0.112	0.24 0.17	1.92 2.72
4	South end of roof ridge. Mounted for north-south pickup	0.115	0.27 0.21	1.92 1.07

a. All flights F-101 except 6 F-106 flights.

b. Overpressure for flights producing each high reading. Δp range for all 120 flights: maximum 2.99 psf; minimum, 0.036 psf; average, 1.16 psf.

cracking is audible. Such cracking is not an ordinary occurrence, nor is knowledge of the cracking noise general. This lends credibility to those claims during the Oklahoma City tests in which the cracks were said to be heard or seen. Of 60 sample paid claims of all types, two reported hearing plaster crack; of 60 rejected claims one so reported. Total claims number nearly 4000. An example of such a case indicating the problem facing investigators is this

extract from an investigator's report: "She /the claimant/ could not see the ceiling crack which had been observed to open and I could see no crack."

It would appear then that the upper-story ceilings of a significant portion of the residential structures in the United States have only a marginal resistance to sonic boom cracking from excessive deflection.

The only measurements of racking displacements from the FAA program are those for the upper northwest corner of the second story of House 5. For 120 flights during July, the east-west displacement from rest averaged 0.112 in., the peak readings being 0.24 and 0.17 in. Assuming that this was distributed uniformly over the height of the house, the displacement at the top of the first story would have values half those above, or 0.056, 0.12, and 0.085 in. These would be the amounts of racking motion in the east-west direction of the north wall of the house. Tests have shown that the plaster of a wood-framed (wood lath) wall may crack from movements at the top plate of only a few hundredths of an inch.[20, 62]

House 5 displacement measurements (Table 5-2) indicate that an old house of this type with wood lath plaster would definitely be subject to plaster cracking. The visual observations in House 5 during July in fact do show new cracks or extensions of old ones almost daily.

As Table 5-3 indicates, nail popping through the plaster board "dry wall" interior surfaces of Houses 1, 2, 3, and 4 was reported continuously throughout the test period. Nail popping is a common problem, whose basic causes are completely unrelated to the sonic boom. One is improper application procedures such as nails insecurely driven, framing twisted or out of alignment, and board not nailed to firm contact. A second one significant to this study is lumber shrinkage.[56, 57, 72, 73] If a nail is driven to the midpoint of a 2 by 4 stud along the 4-in. center line during framing, nearly 1/8 in. of the shank will emerge from the wood after a 10 percent loss of moisture content. The nailed material will then either remain in contact with the wood with a resulting nail pop, or the nailed material will move with the nail.

It appears likely that the sonic boom inside overpressure recurring eight times daily at Oklahoma City could have contributed to producing the pops through the repeated push-pull of the N-wave on the walls. This action would push the board to contact with the framing. Although the trade agencies interested have developed techniques to eliminate or minimize pops, a considerable increase of nail pops appears likely as occurred in Oklahoma City, when SST operations begin.[54, 55]

TABLE 5-3

SUMMARY OF VISUAL OBSERVATIONS

IN TEST HOUSES 1, 2, 3 & 4

	Feb.	Mar.	Apr.	May	June	July	Aug.	Total
Foundation								
Settlement	2	-	1	-	-	-	-	3
Structural, exterior								
cracks, new	-	-	2	3[a]	4[b]	6	3	18
cracks, extension	-	-	-	1	1	2	2	6
Mortar or seal separations	-	-	-	-	-	2	19	21
Structural, interior								
loosening screws or molding	-	1	-	-	1	-	-	2
Wall surfaces								
plaster cracks	-	-	1	-	-	-	-	1
plaster falling off around nail	-	-	-	-	-	-	-	1
paint cracks or peeling, new	-	3+[c]	4+[c]	4+[c]	4+[c]	4+[c]	4+[c]	23+[c]
paint cracks or peeling, extensions	4	4+[c]	7+[c]	11+[c]	5+[c]	4+[c]	4+[c]	39+[c]
nail popping through paint on wall boards	-	4+[c]	4+[c]	4+[c]	4+[d]	4+[c]	4+[e]	24+[c,d,e]
tile, grout cracks, new	-	-	1	-	-	4	2	7
tile, grout cracks, extensions	-	-	1	-	4	1	-	6
tile chipping	-	-	-	-	-	1	-	1
wood cracks, new	-	-	-	-	1	1	-	2
Glass								
cracks, new	-	-	-	-	-	-	1	1
cracks, extensions	-	2	1	3	-	1	-	7
Electrical equipment								
tv out of adjustment	-	1	4	2	4	-	2	13
air conditioner broken down	-	-	-	-	-	2	7	9
misc. (circuit breakers off, tv antenna broken during night, refrigerator off, static on radio, buzzer going on oven timer)	-	1	-	-	-	1	3	5
Furnishings								
light fixture cracked	-	1	-	-	-	-	-	1
hung mirrors cracked	-	3	-	-	-	3	1	7
bric-a-brac (plastic trim "checking"	-	-	-	1	-	-	-	1
movement of chrystal stems on shelf)	-	-	-	-	1	-	-	1
Misc.								
furnace or water heater pilot out	-	1	-	1	-	3	-	5
sewer backed up	-	-	-	-	-	-	-	-
front door lock jammed	-	-	1	-	-	1	-	2

a. "several"
b. 1 plus "cracks"
c. extensions of existing and appearance of some new paint cracks and nail poppings "continue sporadically"
d. "considerable increase" in new nail popping
e. "large number"

5.1.3 Effects on Glass

The range of stresses at failure of glass under loadings of different duration is indicated in Table 5-4, showing possible sources of such loadings.

TABLE 5-4

GLASS YIELD STRESSES FOR VARIOUS LOAD DURATIONS[a]

Duration	Nominal Yield Stress, Large Panels, psi: Window	Plate	Heat-treated	Possible Load
0.1 sec	6,600	6,000	15,000	Boom, blast
5-10 sec	6,050	5,500	13,750	Wind gust
60 sec	4,400	4,000	10,000	"Fastest mile wind" [b]
2 hr.	3,300	3,000	7,500	Long term

a. See Ref. 47
b. Highest wind velocity which endures at least one minute.

The limited observation and experiments of boom effects on glass made prior to the Oklahoma City test program (see Appendix A) did not permit verification of the damage thresholds in the range of SST overpressures. Little additional insight into this problem was gained through the Oklahoma City test program. Considerably more sophisticated instrumentation than was used would have been necessary, as well as a greater range of overpressures. The highest strain readings obtained on the 36 by 82-in. glass door panel in House 1 ranged from 25 to 35 micro-in. per in. For a modulus of elasticity of 10.6×10^6, the resultant indicative stress values of the order of 250 to 350 psi are quite small relative to an allowable stress level of 6600 psi. Similar measurements during July on a 36 by 36-in. window produced strains approximately half those in House 1.

In an effort to induce failures, several window and door glass panes in Houses 1 and 2 were stressed or damaged on February 22 and 23. Several BB holes were made (although not near the probable points of maximum stress) in three panes. Two were scored diagonally with a glass cutter, one on the interior, the other on the exterior. Several panels and the sash were stressed by application of turnbuckles and wire, applied parallel or diagonal to the edges. The extent of the stressing was not measured. No failures were induced, except for the extension of cracks resulting from the BB shooting.

Visual observations of the glass in all four of the test houses throughout the booming and in seven others during most of July produced only two reports of any window breakage not definitely attributable to other cause. Both occurred in House 5. A 24 by 24-in. second-story window glass (orientation not identified, but E, W, or S) cracked in the lower right corner on July 13. A 24 by 30-in. first-story window glass facing southwest developed two cracks.

The observer "believed that these cracks occurred between 7 July 1964 and 9 July 1964." Overpressures measured at the house on July 7, 8, and 9 exceeded 1.4 psf in four of 24 flights (1.89, 1.67, 1.54, and 1.49).

Since no other apparent cause was suggested by the observers, there is a possibility of boom causation. Possible contributing causes, such as installation stresses, may have existed.[68]

A special investigation was made in June of the 32-story, 407-ft. high First National Building, about six miles from the flight track. Its operators had alleged sonic boom cracking of 42 of its 1723 windows, all of nominal 1/4-in. glass, mostly about 3 by 4 ft. A more detailed survey revealed a total of 105 cracked windows, 29 of which were in areas not included in the original survey.

During the week of the survey, the average overpressure at House 3, about a mile closer to the track, was 1.70 psf. Special measurements were taken about the First National Building. The groups of these with higher overpressure values are shown in Table 5-5. An effort was made at the corner insets to measure reflective multiplication. The reentrant corners facing southwest would have been the most likely locations for the maximum reflection. The measurements do not indicate that it occurred to any significant extent. The average overpressure values are in line with those for the week. The maximum values are typical of those resulting from meteorological low-altitude turbulence.

TABLE 5-5

FIRST NATIONAL BUILDING OVERPRESSURES

Location	Floor	No. of booms	Overpressure, psf Maximum	Overpressure, psf Average
N W Corner inset	29	4	2.53	1.73
S W Corner inset	29	4	2.22	0.73
S W Corner inset	27	4	3.02	1.84
N W Corner inset	27	4	1.84	1.38
West wall	14	8	1.33	1.07

The stresses corresponding to the peak deflections ranged from 98 to 342 psi. These values are small compared to 6000 to 6600 psi allowable. No windows were reported broken during the special survey. Of the breakage found at the start of the special survey, investigators concluded that

(1) boom damage to properly installed windows of the types used was unlikely, and

(2) the boom could contribute to cracking of some improperly installed, damaged, or inferior-strength glass in the building.

As of October 1, 1964, 53 Oklahoma City claims had been paid for window glass and 14 for plate glass. These represented 38.3 percent of the total of 175 claims paid.

[redacted]

Although the investigators were in most instances dubious, the claims were paid since in many claimants made sworn statements to the effect that the breakage was witnessed simultaneously with the boom.

It appears that properly installed window panes of smaller sizes, such as most residential glazing, should not fail from overpressures of 1.5 to 2.0 psf whether produced by existing aircraft or the SST. A small incidence of breakage may occur in windows pressured from installation or other causes. Nevertheless the threshold for breakage of such panels has not been clearly identified, and for at least one supersonic aircraft type lies below 20 psf. Experimentation to define the threshold is desirable.

Large panels that vibrate at 5 to 20 cps (see Figure A-4 of Appendix A) apparently can fail from booms produced by current supersonic aircraft. The longer period of the SST sonic boom will increase the vulnerability of glass panels at the low end of the frequency range (2 to 5 cps), by increasing the frequency ratios to levels associated with significant stress amplification (see Appendix E). Nevertheless further investigation is needed of glass stresses and damage in connection with vibratory responses.

5.1.4 Miscellaneous Effects

An analysis of readings at 15 accelerometers in House No. 1 for 329 flights is contained in Table 5-6. The values averaged for June do not exceed 0.40 g. A relatively small, but significant, number of observations fell between 0.50 and 1.0 g. and in one reading attained 1.18.

Peak values for the top house corners (gauges 1, 3, 4, and 5) exceeded 0.17 g in only one instance. at 0.33g. A living room exterior wall stud (gauges 6 and 7) was subjected to g values normal to the wall exceeding 0.50 in several cases: 0.89, 0.88, 0.74. These accelerations would be transmitted to any objects attached to such a wall, such as, for example, a china and crystal filled built-in cabinet. In a pattern which parallels the British investigations reported in Appendix A, roof rafter accelerations (gauges 8 and 9) in many instances exceeded 0.50 g, for example. g values of 1.18, 0.94, 0.93, 0.81, and 0.76 were measured during July, although none during the earlier months had exceeded 0.60 g. Here too chattering and displacement of brittle roofing materials (tiles and slates) is possible. The likelihood that insecurely fastened roof sections will move also needs further study.

A detailed listing of the visual observations in the test houses is available in the monthly progress reports to FAA and a summary thereof by category of observation is in Table 5-3. Correlation of damage with sonic boom is hindered due to the current deficiency in accurate knowledge of boom effects and thresholds of boom damage. This deficiency also plagued claims adjustment personnel.

[redacted]

[redacted]

TABLE 5-6

HOUSE 1 VIBRATIONS: AVERAGE AND PEAK ACCELERATIONS FOR A SAMPLING OF FLIGHTS [a]

Month	Aver. Δp,[b] psf	Aver. Pos. Impulse, lb-sec/ft²[b]	Accelerometer Peak Values, g, and No. of Readings ( )															Averages for No. 14
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Feb. (3 - 29)	1.087	0.0264	0.05 (28)	0.15 (32)	0.09 (32)	0.06 (32)	0.09 (32)	0.30 (33)	0.25 (33)	0.50 (33)	0.27 (32)	0.12 (32)	0.18 (33)	0.17 (33)	0.38 (32)	0.47 (32)	0.33 (32)	0.28 (32)
March	1.112	0.0236	0.11 (84)	0.15 (86)	0.14 (86)	0.10 (86)	0.14 (86)	0.89[c] (86)	0.41 (86)	0.45 (79)	0.31 (86)	0.17 (85)	0.39 (82)	0.18 (83)	0.35 (56)	0.50 (86)	0.35 (85)	0.32 (86)
April	1.160	0.0250	0.07 (48)	0.12 (49)	0.13 (49)	0.06 (49)	0.12 (42)	0.74[d] (49)	0.30 (30)	0.44 (47)	0.41 (49)	0.23 (47)	0.35 (43)	0.23 (46)	0.44 (47)	0.76 (48)	0.50 (46)	0.37 (48)
May	1.171	0.0384	0.06 (52)	0.17 (52)	0.10 (54)	0.05 (54)	0.17 (54)	0.32 (54)	0.31 (47)	0.42 (54)	0.47 (54)	0.12 (54)	0.26 (54)	0.18 (52)	0.31 (54)	0.51 (54)	0.35 (54)	0.33 (54)
June (peak)	1.489	0.0516	0.07 (58)	0.11 (61)	0.10 (61)	0.07 (61)	0.08 (61)	0.26 (61)	0.44 (61)	0.59 (60)	0.46 (60)	0.18 (60)	0.33 (58)	0.16 (57)	0.37 (57)	0.67 (58)	0.54 (61)	0.38 (58)
Averages in June			0.03	0.06	0.05	0.03	0.04	0.15	0.20	0.23	0.15	0.06	0.10	0.07	0.24	0.38	0.36	
July	1.580	0.0536	0.33[e] (31)	(0)	0.09 (2)	0.07 (30)	(0)	0.88[f] (30)	0.37 (27)	1.18[g] (24)	0.22 (2)	0.19 (25)	(0)	0.08 (2)	(0)	0.49 (29)	0.45 (31)	0.36 (29)

a. Data on 329 flights available for this study.
b. Averages of all flights made.
c. Other values ≤ 0.4.
d. One 0.67; others ≤ 0.38.
e. Except for this peak value, the remainder during July were in the range of values of the earlier months.
f. Other values for July ≤ 0.28.
g. The average for July was 0.53; the following additional values ≥ 0.70: 0.94, 0.93, 0.81, 0.76, 0.70.

[redacted]

Foundation settlements and exterior cracking were frequently observed and were a frequent claims item as well. The likelihood of such effects from the boom appears small considering the negligible ground motions and small building movements. For example, Table 5-2 indicates that the maximum displacement at the top of the second story of House 5 was only 0.24 in. The more likely cause in Oklahoma City was the red clay soil on which Oklahoma City is built. It is subject to substantial changes in volume as the water content varies. Buildings with light foundation loadings on shallow foundations, e.g., houses without basements, are particularly susceptible to movement as soil volume changes.

Twelve malfunctions of electrical equipment using vacuum tubes (TV, radio) were observed. These could result from vibration-induced breakage of filament connections and similar non-rugged features. Solid-state and ruggedized equipment would be far less susceptible. Reports of damage to few bric-a-brac and furnishings indicate possible damage to such items where weak attachment or risky placement permits dislocation through vibration.

The distribution of claims paid during the Oklahoma City test program by type of damage as of October 1 is compared in Table 5-7 to a group of St. Louis claims considered "probably or possibly valid."

In Oklahoma City, as in St. Louis, there is probably some question as to the validity of certain of the claims paid. No structural damage claims were paid. Many glass

TABLE 5-7

DISTRIBUTION BY TYPE OF DAMAGE OF SELECTED CLAIMS

Type of Damage	Oklahoma City		St. Louis	
	No.[a]	Percent	No.[b]	Percent
Auto glass	3	1.7		
Window glass	53	30.3	10	37.0
Plate glass	14	8.0		
Plaster and plaster board	80	45.7	6	22.3
Plaster and glass			3	11.2
Cracked porcelain	3	1.7	2	7.3
Bric-a-brac	5	2.9	5	18.5
TV	1	.6		
Light fixtures, lamps, mirrors	10	5.7		
Structural			1	3.7
Miscellaneous	6	3.4		
	175	100.0	27	100.0

a. Claims paid to October 1, 1964.
b. Considered "probably or possibly valid."

damage payments were made with little examination of the causal relationship beyond the claimant's statement that there was an eyewitness to breakage coincident with a boom. This avoided any questioning of the claimant's veracity and hastened disposition of many claims in small amounts. Glass and interior wall surfaces constituted the bulk of all claims.

Also of interest for claims experience is the fact that of about 3900 claimants, 28, or less than 1 percent, were clearly identifiable as non residential. There were perhaps a few individually operated enterprises not identifiable as nonresidential. The distribution reflects in part the preponderance of residential buildings (76.3 percent of the assessed value of all buildings in the area) but it also results from the higher standards of design and maintenance for nonresidential structures, by virtue of which they are less susceptible to damage.

5.2 EFFECT OF AIRCRAFT CHARACTERISTICS ON STRUCTURAL RESPONSE

The time-pressure characteristics of a sonic boom depend on the configuration of the aircraft (length, weight, shape, etc.), on its flight conditions (altitude, speed, variations from steady flight conditions, etc.), and on atmospheric conditions. The competing manufacturers are striving, consistent with other design objectives, to minimize the boom level of their aircraft designs.[6, 24, 38]

For a given aircraft configuration, the overpressure produced in steady flight or in controlled and uniform acceleration, deceleration, climb, or descent is a direct function of speed and an inverse function of altitude.

The pressure wave length (i.e., the duration of the pressure variation) depends mainly on the aircraft length, speed, and altitude; near the aircraft it is equal to the aircraft length, and on the ground it is 3 or more times as long as the aircraft when the aircraft is at SST cruise altitude.

Since the impulse is the area under the time-pressure curve, its value will vary with wave time and pressure. For two pressure waves with the normal N-wave shape and the same overpressure level, the impulses will be proportional to the time periods regardless of which aircraft produced them.

Let us compare the effects of SST sonic booms on the responses and damage levels described earlier in this study. As was indicated in Section 5.2.1 (and elaborated in Appendix D), stresses approximate a linear function of the overpressure loading regardless of the combination of variables (including aircraft characteristics) which might have produced a given overpressure. To put it simply, a roof rafter bearing a 2 psf load does not know what kind of airplane produced it. Although this statement appears to be fundamentally true, there are some limitations.

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Since the boom is a dynamic, rather than a static, load, the degree of stress amplification may vary with the loading duration. However, as Appendix E explains, the differences in the stress amplification during dynamic loading would, for the types of structural panels and elements in the test houses, vary only over a small range (1.6 to 2.0 psf). Accordingly, stresses and damage effects from the SST would be expected to be of the same general nature and magnitude as those from other supersonic aircraft operating at the same overpressures.

Appendix E indicates that very large glass panels will be more susceptible to damage during SST operations due to the greater duration of its pressure wave. Although some large plate glass panels have been broken as a result of vibration induced by present aircraft, these aircraft could not excite such vibratory response in the largest panels currently being installed, whose natural frequency ranges between 1 and 5 cps. However, the SST wave can double the stresses induced in such panels.

5.3 SHOCK WAVE EFFECTS ON FOREIGN BUILDING TYPES

The general nature of housing throughout the pertinent portion of the world is shown in Table 5-8. Western type of structures in these areas fall into two principal categories. In a relatively few "lumber economy" countries, lumber is used extensively for framing the entire structure. These would be countries adequately endowed with lumber resources and not troubled with problems such as deterioration, infestation, and maintenance. In the area under study, these include North America, the Scandinavian peninsula, Japan, and Korea. Except in North America, wood use for construction is diminishing. In the remaining areas, masonry structures (stone, or concrete, or tile blocks) predominate. Roof framing and, in some cases, floor framing may be of lumber. The strength of this construction should eliminate or minimize plaster problems. The window situation would be about as in the United States.

In Western type of countries or communities there would thus be two levels of damage potential, the "lumber-and-glass" level, and the "glass-only" level.

Throughout the tropical areas, damage potential in simpler structures of traditional or primitive types should be minimal because of the open structures and lack of plaster and window glass. Moreover, shock waves will tend to be absorbed in panels of thatched or woven grasses and the like. In the temperate regions, glass is used and may have a potential for damage. Glazed paper panels and window openings used in Japan may present a problem. Tile roofs may suffer the clatter cited earlier. In general, the potential for damage would appear greatest in North America, at a mid-level throughout most of Europe, and be at a minimum in the underdeveloped tropical areas.

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TABLE 5-8

MATERIALS AND STRUCTURAL CHARACTERISTICS OF FOREIGN RESIDENTIAL CONSTRUCTION[a]

Area	Characteristics of Construction				
	Western Type	Regional Type			
		Framing	Wall Types	Roof Types	Use of Glass or Plaster
Africa					
South Africa	Masonry: brick and concrete; glass	Pole and Brushwork	Thick mud; sun-dried bricks	Thatch or thick mud	None
Central Africa	Masonry: brick and concrete; glass	Pole frames raised on pilings	Thatch or mud, almost no windows	Thatch or mud matting on wooden beams	None
Northern Africa	Masonry: stone concrete and bricks; glass	None	Stone or mud, small openings. Cloth tents	Thatch	None
Europe					
Southern Europe	Masonry: brick and tile, concrete; glass	None	Dried clay bricks and terra cotta	Tile	Lathe and plaster interiors, glass windows
Western and Central Europe	Masonry: some plaster and timber halfwork,[b] glass	None	Brick, stone, concrete and stucco	Tile, slate	Lathe and plaster interiors, glass windows
Northern Europe	Masonry: brick and concrete; woods, glass	Wood framing	Substantial wood, sometimes logs. Some brick and stucco	Tile, slate	Plaster interiors, and glass windows
South America					
Tropical	Masonry: adobe, tile; wood[b] glass	Posts of bamboo or wood	Wattle and daub, grass or straw, almost no windows	Clay tile and thatch	None
Temperate	Masonry: brick and adobe, glass	None	Strong mud and substantial adobe, brick	Heavy tile, metal, straw	Plastered interiors in colder areas, glass windows

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TABLE 5-8

MATERIALS AND STRUCTURAL CHARACTERISTICS OF FOREIGN RESIDENTIAL CONSTRUCTION[a]—Continued

Area	Characteristics of Construction				
	Western Type	Regional Type			
		Framing	Wall Types	Roof Types	Use of Glass or Plaster
Central America	Masonry, adobe; wood,[a] glass	Wood pole framing	Wattle and daub, adobe, thatch	Cane straw or leaves	None
West Indies	Masonry, concrete; brick; wood,[a] glass	Some wood framing	Concrete, brick, wood	Tile, concrete, straw	None
Asia					
Asia Minor	Masonry: fired brick; glass	None	Sun-dried bricks, adobe, stone; almost no windows	Mud-brick domes on flat reed matting covered with straw and clay; clay tiles	None
Southeast Asia	Masonry: concrete, tile; wood,[a] glass	Bamboo and wood frames on pilings	Bamboo, other temporary vegetable matting materials; few open windows	Leaves and other thatch; some tile	None
India-Pakistan	Masonry: brick; some wood,[a] glass	Bamboo frames	New bamboo and reed; open windows	Thatch or mud, some tile	None
Far East	Masonry: concrete; wood,[a] glass	Wood frame	Wood; glazed paper windows with wooden shutters	Tile	None

[a]From Refs. 27, 53, 63, and 64, the Encyclopedia Brittanica (1959 ed.), and other sources.

[b]In many areas where Western-style houses were once made of wood, they are increasingly being replaced with masonry ones.

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LIABILITY FOR SONIC BOOM GROUND DAMAGE

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LIABILITY FOR SONIC BOOM GROUND DAMAGE

Section 4 dealt with the tradeoff between the cost of claims for ground damage from SST sonic booms and the added cost of modifying SST operations so as to decrease the cost of claims. On the assumption that the total system cost is the sum of operating and damage costs, the major effort of this study has been toward minimizing the latter. It must be emphasized, therefore, that our estimates of the cost of processing and paying claims are based almost entirely on the data collected by the FAA at Oklahoma City in 1964. The Federal government, which conducted these experiments, assumed liability under the existing laws to pay valid claims. This was in line with Air Force experience over the past ten years, during which time claims resulting from sonic boom damage were paid, either wholly or partially, if they were determined to be valid. We have assumed that a liability for damage from SST sonic booms will exist and will increase system cost.

Court decisions involving liability in similar situations have been cursorily examined. It is not clear from this side study that an airline (or the Federal government, for that matter) would be liable for sonic boom damage to persons or property on the ground resulting from the operation of a properly certificated commercial transport, flown in accordance with procedures prescribed by the Federal government.

Several kinds of damage might result from these operations: physical damage to ground structures, loss in property values, damage to domestic animals, direct physical injury to humans, indirect physical injury to humans, and mental harm or injury to humans. There are precedents which suggest that claims for each of these classes of damage would be treated quite differently by the courts. It seems reasonably clear that an airline operating a supersonic aircraft in a negligent manner would be liable for resulting damage but it would be difficult to predict either the court's definition of "negligent operations" or what a court would accept as proof of negligence.

Like the industry it seeks to regulate, aviation law has been expanding and evolving to deal with issues and problems raised by new technological developments. The prospect of airline liability for sonic boom damage raises hard questions of law because a novel source of damage is

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involved and existing theories of aviation tort law do not clearly apply to the circumstances under which damage will occur.

Two approaches toward a theory of liability are suggested.* Both have weaknesses, both can be challenged with sound defenses. Nonetheless, to let the landowner-plaintiff bear the loss seems so unfair that courts are likely to accept either one or an amalgam of the two despite their shortcomings.

First, the courts might extrapolate directly from the extensive body of aviation law pertaining to interference by landing and departing aircraft with landowners' airspace rights and with their use of subadjacent property.

Both the underlying rationale of holdings in this field and their intended scope are unclear. But for the most part, the cases emphasize the plaintiff's property rights in the reaches of airspace immediately above his land and tend to speak in terms of trespass and the "taking" of an easement over the land.

Accordingly, the language in some of these cases suggests that flights at very high altitudes, being in the public domain of "navigable airspace," would not incur liability. The overflights challenged in past litigation generally have been at a few hundred feet; the SST would attain supersonic velocities at about 30,000 feet. Nevertheless, since the equities suggest liability, the novel situation presented by supersonic flight might be held to warrant abandoning the formalistic "layers of airspace" approach in order to protect a property interest, while still claiming legal descent from the low-overflight cases.

Second, the courts might decline to upset the established case law distinguishing damage on the surface caused by low over-flights from the harmful effects of high altitude flights. In that case, a more general nuisance analysis could be applied, thereby avoiding the technical conundrums of what constitutes a trespass or a "taking." Supersonic aviation would be treated like any other nuisance-producing industry.

The main obstacle to liability on the part of the airlines from this approach will be the intense degree of government participation and regulation of both the SST's development and its commercial operation. This amount of Federal involvement in determining the existence, the nature, and the extent of supersonic aviation makes the enterprise a strong candidate for the protected status of "legalized nuisance," i.e., one whose harmful effects

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*We have rejected absolute liability on the part of the operator. Such an approach might be based on the legal theory that the pressure wave generated by the supersonic transport in non-negligent flight is a "physical" extension of the aircraft itself.

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would result in liability if its operation were not so extensively planned and regulated by the government.

Here again, the courts' reluctance to burden the landowner could produce a finding that Federal involvement was relevant only in allocating responsibility between the government and the airlines, not in deciding plaintiff's right to compensation per se. Such a finding could result in one of several decisions. Damages might be awarded against the airlines. Damages might be awarded along with a decision that the airlines might seek a contribution from the government. Finally, the court might decide that the government was the sole proper defendant.

Finally, the question whether the airlines or the government is liable is all the more important because it may influence the acceptance of SST operations by the American public, and because it may occasion a need for a proper mechanism to process and adjudicate claims if liability if found to exist. It might be argued, for example, that a clear holding of liability on the part of the airlines and the Federal government would go a long way toward satisfying offended citizenry. It might be that payments to individuals would stop political actions by states and municipalities seeking to limit or even prohibit offending supersonic transport operations. In this event, however, some mechanism would be required for processing the large number of claims that would presumably result. As shown in Section 4 of this report, one-third to one-half the population of the US would be subjected to sonic booms.

Our preliminary study of liability has led us to no definitive conclusions or recommendations. However, we have explored the problem sufficiently to conclude that the question should be explored in depth as part of the SST development program. For if no liability is found to exist, claims costs would be negligible; if liability is found to exist, not only for physical damage, as in the case of Oklahoma City, but for other classes of damage such as loss in property value without physical damage, the resulting claims costs could be much higher than the Oklahoma City level. Because of the importance of the problem, we recommend that the entire question of liability for damage claims be carefully explored. If it is concluded that liability will exist, the procedural mechanism for processing and paying claims should also be studied.

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APPENDIX A

STRUCTURAL RESPONSE DATA TO SONIC BOOM COLLECTED PRIOR TO THE OKLAHOMA CITY PROGRAM

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APPENDIX A

STRUCTURAL RESPONSE DATA APPLICABLE TO SONIC BOOM COLLECTED PRIOR TO THE OKLAHOMA CITY PROGRAM

Prior to the Oklahoma City test program, knowledge of sonic boom effects on buildings was based on information from these sources:

(1) Well-publicized incidents resulting in extensive damage to buildings (Discussed briefly in Sec. B. 1)

(2) A limited number of sonic boom experiments in the United States and the United Kingdom (Sec. B. 2)

(3) Theoretical and related field investigations not necessarily directed toward sonic boom (Secs. B. 3, B. 4, A. 5)

(4) The St. Louis Flight-Test Program (Sec. A. 6)

A. 1 SONIC BOOM INCIDENTS

An early example of sonic boom damage occurred on April 10, 1957 when an F-100 airplane made an accelerating dive of some 12,000 feet over Cedar City, Utah, passing over the city at an altitude estimated variously from 500 to 2000 feet. Within an area about eight blocks by five blocks, damage attributed to the boom included: hundreds of broken windows, plaster damage (thirteen claims), several 2-by-10-inch members forming the bottom chord of 50-foot wood trusses split at their center lines and the corrugated metal roofing thereon lifted and shifted six inches, and several dropped light fixtures.[1]

On October 30, 1958, an F-105 airplane made a supersonic pass at 100 to 200 feet over Tyndall Air Force Base, Florida and then went into a decelerating climbing turn. As a result, \$20,310 was paid for damage to an area of several blocks in Panama City, eight miles away and in line with the runway axis. The damage included 52 broken plate-glass windows.

In the summer of 1959, the boom from an F-104 airplane over Ottawa's airport terminal building necessitated repairs costing over \$500,000. Over 90 window panels (ranging from 4-by-8 to 8-by-16 feet) were broken, many aluminum window frames were racked, prefabricated curtain wall sections were cracked and broken, built-up roofing was torn and plowed so badly that full replacement was necessary, and over 50 percent of the interior 3/4-inch acoustical tile ceiling had to be replaced.[2]

In addition, the US Air Force has found it necessary to pay out about \$775,000 during the past ten years for damage claimed to have been caused by sonic booms. Throughout that period there had been but little systematic

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testing and understanding the effects of sonic boom on buildings.

A.2 SONIC BOOM EXPERIMENTS

The first American observations were made in 1958 at Wallops Island, Virginia by personnel of the NASA Langley Research Center. Coincident to some ground-pressure measurements, it was noted that a 90-by-128-inch, 1/4-inch-thick plate-glass window was cracked parallel to its short edges by an overpressure estimated to be 1.75 psf. However, localized focussing or corner reflection may have produced a higher value. The long edges, which were secured by mullions, were less firmly supported than the short edges. Furthermore, the sizes of the window and the aircraft (F-101) were such that the resulting frequency ratio could well have produced the maximum stress amplification (see discussion in Appendix E). Whatever the circumstances, this damage was near the breakage threshold, since windows immediately adjacent on each side, which were firmly supported on three edges, did not break.[3]

Langley personnel continued their work in 1960 at Nellis AFB, Nevada, with project "Little Boom." "Little Boom" tested 36-by-36-inch double-strength (about 1/8-inch thick) glass whose fundamental frequency was 28 cps and next vibration modes 47 and 80 cps and which, under static testing, failed at 140 to 160 psf and 0.6 to 0.8 inch deflection. Also tested were colonial windows 36-by-36-inch overall, consisting of nine 11-by-11-inch single-strength lights. The results are presented in the following table. No F-104 tests were made in the 0 to 20 psf range

Overpressure, psf	percent windows broken F-104	percent windows broken F-105
0-20	-	0
20-40	30	0
40-60	50	0
60-80	55	35
80-100	75	50

so that the damage threshold was not indicated. In these tests the aircraft were flown at altitudes of 50 to 900 feet and the pressure waves took the more complex forms usually existing close to the airplane before transition to the more usual N-wave form. The differences in window breakage for the two aircraft were thought to result from major differences in the complex waveforms. Some collateral ground-motion measurements indicated vibrations in the range of 2 to 10 cps with maximum amplitudes of 0.01 inches for high overpressure levels.[4, 5]

Later in 1960, under project "Big Boom," the B-58 aircraft was flown in 16 flights with measured ground pressures up to 2.09 psf. Several of the 36-by-36 windows used in the "Little Boom" tests were observed to have negligible response even after being scribed. Several thermal plate-glass windows approximately 6 by 8 feet were observed to

vibrate and deflect, but without damage. Ground-motion was observed but not reported beyond the comment that it was barely perceptible, though stronger than that produced by low-altitude high-subsonic speed flights such as those of "Little Boom."[6]

In 1961, the primary objective of work by NASA was the distribution of overpressures throughout the affected path, although some ground-motion measurements were included.[7,8] In 1962, at Wallops Station, NASA conducted tests to observe overpressure distributions in a simple building and strains induced in some of its components. These tests, which were a significant step forward, have not been reported by NASA but have been partially presented at various symposia.[9,10] The building was 20 feet long, 40 feet wide, and 10 feet high; for overpressures up to 3.0 psf, pressures were measured on the front and rear surfaces (i.e., the surfaces closest to and farthest from the approaching airplane). Sample time histories are shown in Figure A-1 where the trace for the front face shows the initial rise to the ground pressure peak and the further rise to a peak about twice the ground pressure due to corner reflection. As would be expected, the form of the pressure wave on the side and rear walls differs from that of the front wall due to diffraction as the wave envelopes the building and to lack of reflection as the wave direction parallels a wall.

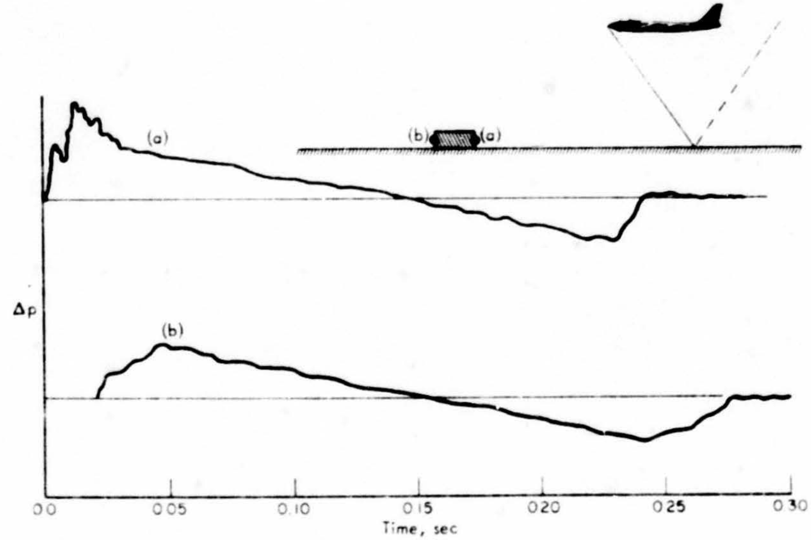


FIGURE A-1 Sample Time Histories of Sonic Boom Pressure Loading on Two Surfaces of Test Building

As indicated schematically in Figure A-2, the translational forces exerted on a building will depend on the relative lengths of the building and the shock wave, as well as on their geometrical relationship. The modes of loading a simple structure are shown in Figure A-3. In these ways as well as through the roof, loadings will be delivered to the interior walls, ceilings, and other structural sections, which will be subjected to similar bending and racking stresses. The 1962 NASA tests measured the stresses induced in various elements of the structure; the maximum value recorded for a stud was about 60 psi (corresponding to a strain of about 35 micro-in./in). This is considerably higher than most stud stresses experienced in Oklahoma

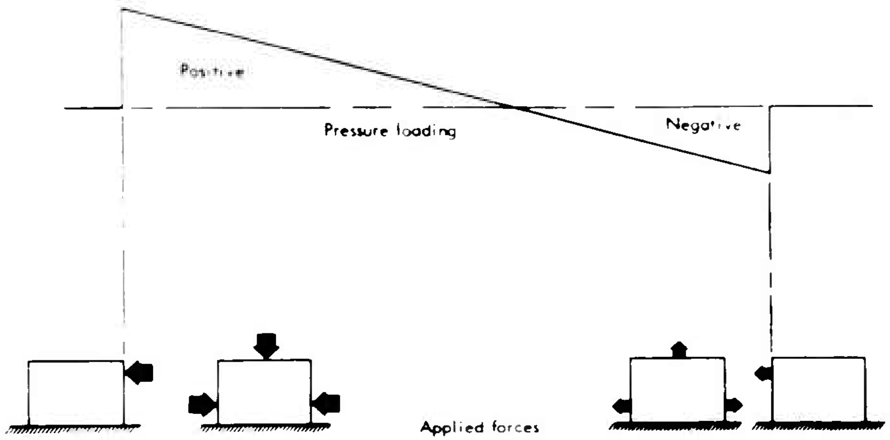


FIGURE A-2 Schematic Diagram Showing Pressure Loadings Experienced by Building Exposed to Sonic Boom

City and probably results from the absence of interior wall surface which would otherwise bear part of the loading.[9,10]

More extensive research than that summarized above had been done as early as 1957 by the Building Research Station in the United Kingdom. The buildings were of brick masonry, with medium-to-steep pitched roofs of tiles or slate, in good repair, of ages ranging from quite old to recent, with roof framing of the British convention (some of roughhewn timbers). During five flights with ground pressures up to 5.0 psf, accelerations (in g's) of a slate roof (35-deg pitch) facing the wave were 0.6, 0.8, 0.9, 0.5, 0.47, 0.8, 1.0, 0.46, 0.42, and 0.6. Those of a tile roof (steep pitch) facing the wave were 0.4, 0.6, 0.5, 0.27, 0.3,

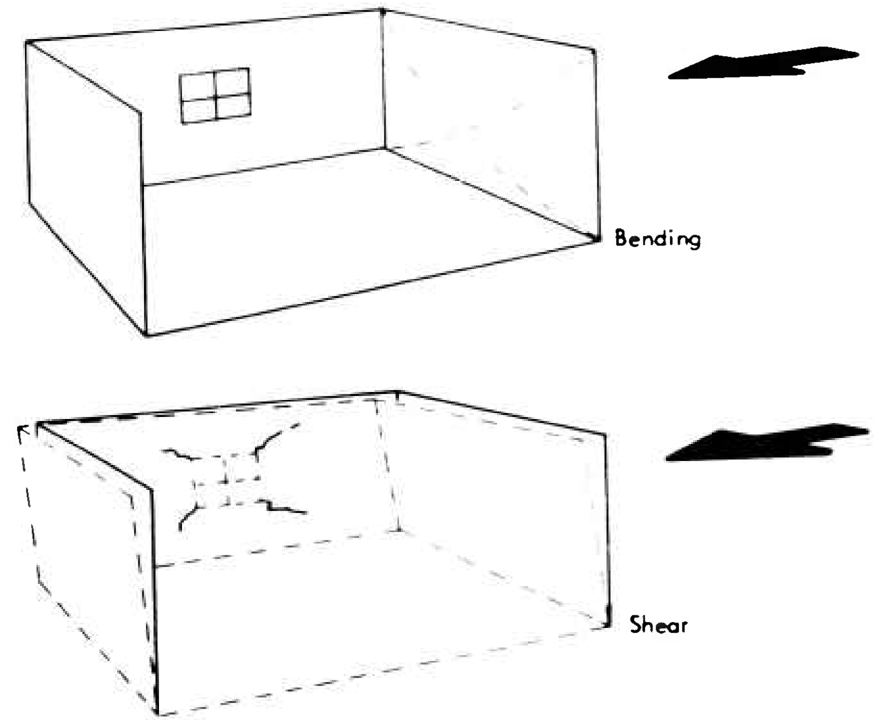


FIGURE A-3 Schematic Diagram of Bending and Shear Loading Modes

0.4, 0.2, and 0.18. The displacements induced are shown in Table A-1, together with the natural frequency period of various elements.

The higher acceleration values (near 1.0 and zero g) were considered to be near the point of causing chattering and displacement of slates and tiles. In some instances, the shock waves induced resonant vibration with displacement in the vibration phase exceeding that during the shock wave loading.[11]

[redacted]

TABLE A-1

HOUSE VIBRATION MEASUREMENTS

Position	Natural period, sec	Max. peak-to-peak amplitude, in.					
		Flt. 1	Flt. 2	Flt. 3		Flt. 5	
				1st N	2nd N	1st N	2nd N
1. Slate roof, facing bang		0.036	0.043				
2. Slate roof, facing bang		0.048	0.052				
3. Slate roof, facing bang	0.075	0.075	0.087	0.053	0.029	0.040	0.028
4. Slate roof, facing bang	0.07	0.038	0.044				
5. House wall, facing bang	0.102			0.0025	0.0033	0.0040	0.0038
7. Slate roof, away from bang	0.067	0.020	0.019	0.013	0.013	0.012	0.008
9. Tile roof, facing bang	0.120	0.048	0.056	0.041	0.027	0.043	0.034
10. Tile roof, facing bang	0.12	0.029					
11. Lintel over window	0.190			0.0041	0.0056	0.0042	0.0034
12. First floor, near wall (horizontal)		0.0051	0.0062	0.0047		0.0037	
13. First floor, near wall (vertical)		0.0076	0.0092	0.0066		0.0073	
		Period of N-wave				0.075	0.101

[redacted]

A.3 THEORETICAL INVESTIGATIONS OF SONIC BOOM

The US Air Force, increasingly involved with damage claims, initiated theoretical studies of sonic-boom response in buildings. In 1956 and 1957 the subject was tentatively approached by the Armour Research Foundation under contract to the Wright Air Development Center, who in 1958 sponsored a more exhaustive treatment by ARDE Associates, an engineering concern of Paramus, New Jersey.

The many assumptions and simplifications necessitated in these studies resulted in closely qualified conclusions of limited utility.[1,12] However, the increasing body of field investigation such as that at Oklahoma City provides a basis for correlating and testing those theoretically derived conclusions.

A.4 OTHER INVESTIGATIONS WITH INDIRECT APPLICABILITY TO SONIC BOOM

A small portion of Atomic Energy Commission nuclear testing has been directed at comparable overpressure levels. Experiments with conventional explosives by the Bureau of Mines and the Army Ballistics Research Laboratory have examined building materials and responses, both to blast and ground vibrations. Finally, in addition to the structures and materials tests of the National Bureau of Standards, there are contributions from the research establishments of a variety of universities (such as the Wood Research Laboratory of the Virginia Polytechnic Institute) and private corporations in their spheres of interest (e.g., the Pittsburgh Plate Glass Company and the U. S. Gypsum Company).

In general, test programs of the Atomic Energy Commission have been concerned with pressure levels markedly higher than sonic boom levels, and few data from applicable experience data are available. In the standard AEC manual, The Effects of Nuclear Explosions, glass windows, large and small, are reported to usually shatter, with occasional frame failure, at an estimated "side-on" reflected overpressure of 0.5 psi or 72 psf.[13] In a more refined analysis of responses in nearby communities, it was estimated that 4 psf would break practically no windows, 14 psf would break 10 to 20 percent, and 86 psf almost 100 percent. These estimated air blast effects correlate roughly with the results of "Little Boom" cited above.[14]

Considerable study and testing of the effects of air blast from explosives have been done by the Departments of the Interior and of the Army. As part of the Interior program, the Bureau of Mines is concerned with commercial blasting operations like mining and quarrying; work by Army deals with the effects of military explosives. Some of the results are cited below. Much of it is of general applicability but difficult to compare to sonic boom effects because the damage effects cited have not been correlated with the overpressure levels resulting from the explosions.[15,16]

There is a substantial body of literature on ground vibrations and responses of residential structures (much of it in the References to Sec. 5). Work in the Bureau of Mines has produced much data on vibration characteristics of the types of residences common thirty years ago.[17] These investigations and other important reports have been reviewed quite recently and analyzed statistically in the Bureau of Mines.[18] The review report recommends, as a criterion for ground-vibration damage, movement at a velocity of 2.0 inches per second. This corresponds to a displacement of 0.03 inches at 10 cps and 0.015 inches at 20 cps. These values are comparable to those established as limits in regulatory statutes of states such as Pennsylvania and New Jersey.[19] By contrast, ground-vibration measurements from the sonic boom shock wave of aircraft operating at 10,000 to 75,000 feet have produced amplitudes of less than 0.001 inches at a frequency of about 10 cps.[7] The low-altitude "Little Boom" tests produced maximum values of the order of 0.01 inches for vibrations of 2 to 10 cps. This compares favorably with the review report's recommended criteria.

Useful test data on the strength of various wood-framed components (walls, roofs, etc.) of residential structures are contained in a number of publications of the National Bureau of Standards. Similar tests have been reported by the Forest Products Laboratory of the Department of Agriculture. These are cited in Sec. 5 of the main text, which discusses sonic boom effects on interior wall surfaces.

A.5 STRENGTH OF GLASS

The work of private and public investigators not concerned directly with sonic boom can be correlated with the response of glass panels to sonic boom. Various investigations have measured loadings, both static and dynamic, to the point of failure.

Some results of destructive testing of glass under static loads are contained in Table A-2. The pressure tabulated for each indicated size was the lowest of those producing failure in the panels of that size. These pressures were maintained over periods as long as 25 minutes, and it was demonstrated with Twindow panels that a considerably higher pressure (twice as high, Orr estimated)

TABLE A-2

STATIC LOAD TESTS TO DESTRUCTION[20]

Size, in.	Thickness, in.	Pressure, psf	Equiv. Wind Velocity, mph
72 x 120	0.114	16.72	72.3
82 x 82	0.240	51.87	158.8
82 x 102	0.2344	36.02	106.1
82 x 120	0.239	23.58	85.8

would be necessary for a load lasting for seconds. It should be noted for the 72-by-120-inch panel, which failed at 16.72 psf, that its size and thickness made it well outside the acceptable criteria for use under current standards. In fact, since a safety factor of 2.5 is common for window design, the 82-by-82-inch panel would, in fact, be rated as acceptable only for about a 20 psf equivalent wind loading.

Table A-3 lists the results of similar testing in the United Kingdom, in which the loading prior to failure lasted about 30 seconds. Although most of these laboratory samples are thicker for their size than glass in normal use,

TABLE A-3

PRESSURES AT FAILURE FOR 41 X 41-INCH GLASS PANELS[21]

Sample	Thickness, in.	No. of Tests	Pressure, psf Mean	Pressure, psf Std. Deviation
1/8 plate	0.122	40	108.0	18.2
3/16 plate	0.197	30	203.0	35.4
window	0.110	30	99.5	13.9
window	0.158	30	197.0	30.5
window	0.195	30	275.0	54.6

the two thinnest panels approximate those which under current standards would be selected for a design load of about 40 psf.

Some tests have shown the greater strength properties of glass with loadings of shorter duration. For example, the tensile breaking strength of 1/4-inch glass rods was found to vary with duration of stress as follows:

Duration	Destruction stress, psi
0.01 sec	20,000
10 sec	10,500
278 hr	6,500.[22]

Experiments with window glass to determine the effects of rate-ot-pressure rise produced interesting results. At a pressure-rise rate of 700 psf/sec, a 14-by-19-inch single-strength glass was broken with about 300 psf; at a pressure rise rate of 5000 psf/second, the same glass was broken at about 700 psf. The comparable breaking pressures for double-strength glass were about 850 and 450 psf. The corresponding loading times to destruction are of the order of 0.01 second. This is markedly shorter than sonic-boom loadings, but does indicate the higher dynamic pressures required for destruction.[22]

The Bureau of Mines has conducted some field tests on breakage characteristics of glass subjected to pressure

[redacted]

waves from explosives. Such waves are reasonable approximations of the sonic boom and have been used in the United Kingdom expressly for boom evaluations. Explosion pressure waves lack the vibration response characteristics of the sonic boom, but this was not a factor for the sizes of glass tested. Experiments in both 1940 and 1941 indicated that 1 psi (144 psf) was the damage point for 10-by-12-inch single-strength panes. At 0.9 psi, the six lights of a window box were undamaged, except those glazed only with glazier's points (in which case breakage began above 0.7 psi). The report concluded that, based on exposures of 150 10-by-12 lights, 2 of 15-by-24, and 1 of 24-by-31, all in five tests, the damage pressure for such glass must exceed 100 psf (0.7 psi).[23]

In studying dynamic loadings of glass, the effect of natural vibration in large panels must be examined. Note that with the static loads reported by Orr (Table A-2) 24 psf was required for failure of a 1/4-inch-thick 82-by-120-inch panel, whereas the NASA Wallops Station tests with dynamic loads caused failure of a 90-by-128-inch panel 1/4 inch thick at an overpressure estimated by NASA at 1.75 psf.*

*The NASA sample was firmly supported only along the two short edges, and a corner reflection effect may have doubled the ground overpressure, which may easily have been greater than estimated.

Undoubtedly the push-pull of the sonic boom has a major effect on vibration. If the natural response frequency of a panel matches the N-wave duration, the motion of the panel as it returns to rest after the positive portion of the N-wave has passed may be reinforced by the negative pressure of the remainder of the N-wave. This displacement and the resultant stresses may exceed those of the positive phase of the loading. This expectation is supported by the fact that many of the panels broken at Panama City were broken outwardly. Typically, fragments were not thrown any distance, but dropped to the floor or ground near the window frame. Some theoretical analysis of the vibration response of glass has been made, but further investigation appears needed in this area.[24]

The spread of wave length durations applicable both to fighter aircraft and the SST ranges from 0.05 to 0.5 seconds, corresponding to frequencies of 20 and 2 cps (126 to 12.6 radians per second). As Figure A-4 indicates, these frequencies define a range corresponding closely to that of the natural frequencies of large plate-glass panels in common use today, with the SST frequencies expanding the range to cover the largest size panels. Hoover and Ross[22], in their theoretical analysis, concluded that the maximum deflections in inches per psi shown in Figure A-5 occur where the dimension less parameter

$$C = 2\pi fT$$

(where f = frequency and
T = N-wave duration)

[redacted]

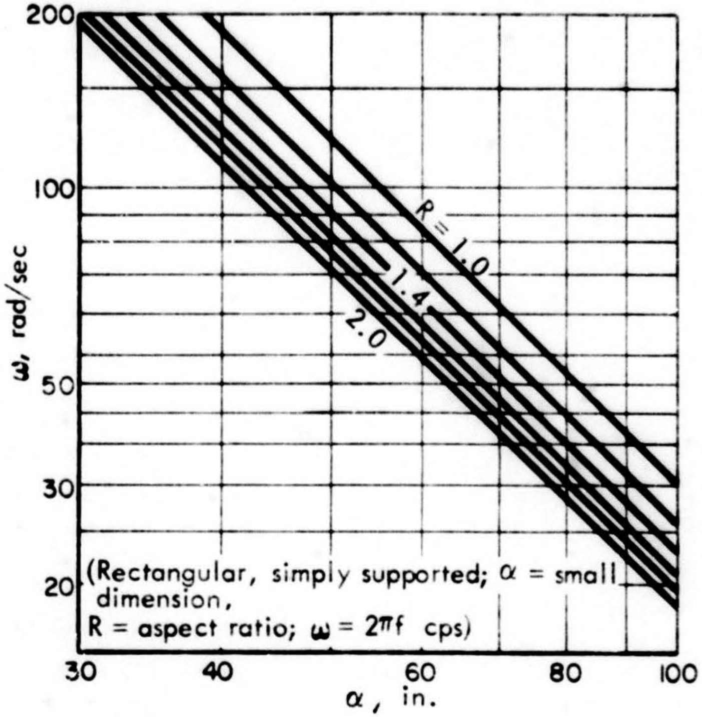


FIGURE A-4 Natural Frequencies of 1/4-in. Glass Panels[24]

has a value of 5.5, or when fT = 0.876. Note that fT is in fact the frequency ratio discussed in Appendix E and that the values are practically coincident. Values of f in this equation correspond to 17.5 to 1.75 for the same aircraft spectrum. Using Figure A-5 the deflection for a 90-by-128 inch panel, similar to that which broke at Wallops Station but supported by all four edges, would be (80 x 1.75)/144 = 0.97 inches. Orr's tests involved a deflection of 1.5 inches at failure of a 96-by-120-inch panel. This may well have

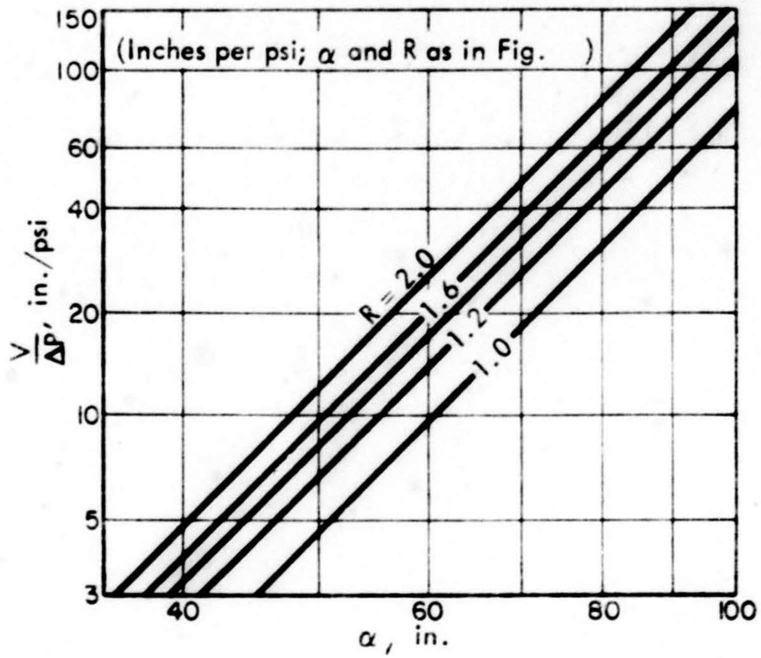


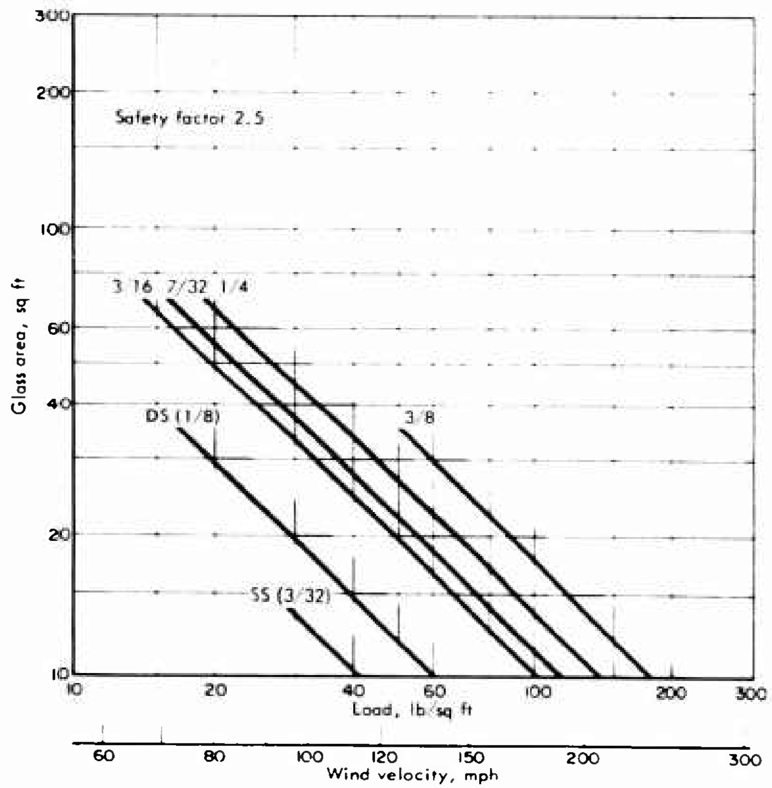
FIGURE A-5 Maximum Deflection of 1/4-in. Glass Panels from Sonic Booms[24]

been exceeded by virtue of the reflection of the 1.75 psf overpressure at Wallops Station to, say, 3.50 psf, or a smaller value may have sufficed since two edges were weakly supported.

Although there is a clear need for further study of vibratory excitation in glass with natural frequencies of 1 to 20 cps, in the absence of natural vibration current design standards more than suffice to prevent glass breakage from SST-boom pressure levels. These standards are

[redacted]

based on static testing such as Orr's.[20] Standards recommended by the Pittsburgh Plate Glass Company, which sponsors research like Orr's, are indicated in Figure A-6. Moreover, building codes specify the wind velocity pressure which design must accommodate, based on wind experience in the specific locality. For the full design load,

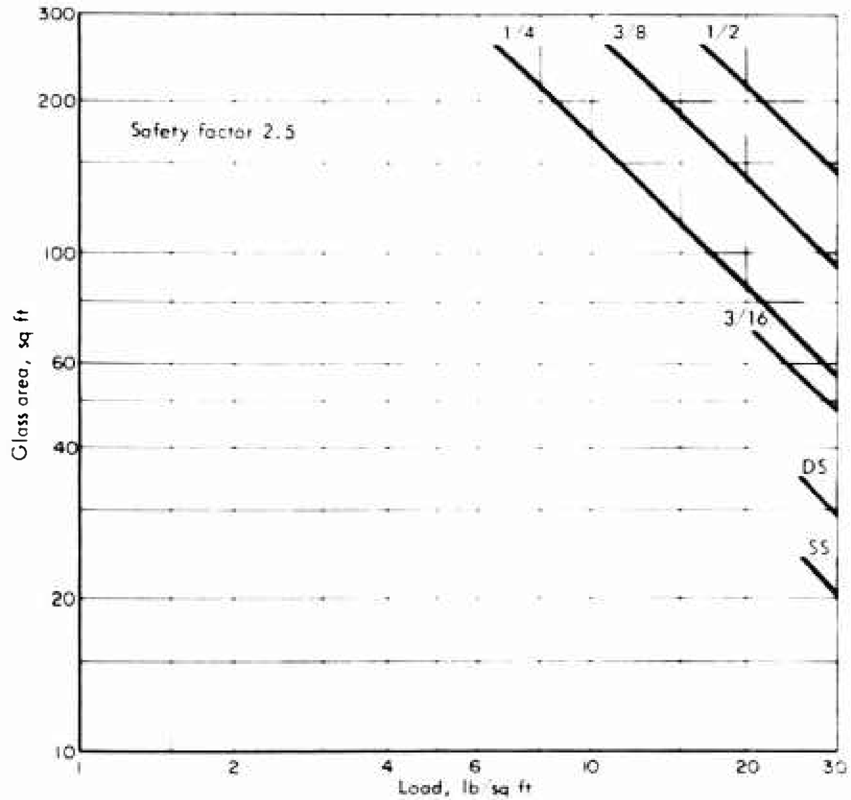


(Normal surface depreciation is taken into consideration. Shading suggests the possible performance of glass with newly formed surfaces. One-minute uniform loading, representative of "Fastest Mile Wind." Support deflection not more than 1/175 span at design load, four edges glazed weathertight. Short side/long side = 1/3 or more.)

FIGURE A-6 Window Glass Design Standards[25]

these standards impose a safety factor of 2.5. As a result, the statistical probability of failure for glass meeting these criteria is 8 per 1000 at the design load, and less than 1 per 1000 for SST overpressures.[25]

The PPG Company has published the design criteria for sonic boom loadings shown in Figure A-7. Since glass



(Normal surface depreciation is taken into consideration. Shading suggests the possible performance of glass with newly formed surfaces. 0.1-second push-pull loading. Support deflection not more than 1/175 span at design load, four edges glazed weathertight.)

FIGURE A-7 Window Glass Standards for Sonic Boom Loadings[25]

[redacted]

is able to withstand greater stresses for the short-duration sonic boom load, the standards shown permit heavier loadings than those in Figure A-6. This shows that unless boom pressures far greater than 2 psf are expected, normal window glass design standards should preclude breakage from SST booms.

A.6 ST. LOUIS FLIGHT-TEST PROGRAM

Once the Federal Aviation Agency was given the responsibility for a national government-industry program leading to SST operations, it apparently recognized the gaps in knowledge about boom effects on people and property and joined with NASA and the Air Force in the St. Louis test program (November 1961 to January 1962). For a variety of B-58 and F-106 airplane flights, ground overpressures were measured. In the structural damage part of the program, damages claimed were inspected or evaluated by engineers. No structural response measurements were made. The St. Louis test program offered the first opportunity to evaluate, in a typical large community, the nature and extent of sonic boom damage.

Table A-4 shows the number and types of damage claims investigated after a special test-flight program in which most overpressures were 2.0 psf (ground track) with a few measurements as high as 3.0 psf. Eighty percent of the claims were for glass and plaster damage, 12.7 percent for wall and foundation cracks. Of the 84 cases investigated by the NASA architect-engineer contractor, 57, or 68 percent, were classed as not boom-induced and the remaining 27 (32 percent) were thought to be either probably or possibly due to the shock wave. Those possibly valid were fresh damage which may have been due to other causes, but for which no other causes were identifiable.

On a generous and conservative basis, then, only 27 of the 165 claims (16.4 percent) presented and investigated had any merit, and it is reasonably certain that some of the 27 were due to other causes. The distribution of these valid claims is notable: 37 percent glass, 22 percent plaster, and 18 percent bric-a-brac.

The St. Louis tests were a substantial forward step in correlating damage cause, overpressure level, and effect. Nevertheless, the conclusions as to structural effects were necessarily extensively qualified. First, prior analyses and investigations had not been sufficient to define, for different materials and structural elements, the response characteristics and magnitudes, damage thresholds, or features distinguishing a specific response from one produced by other causes. Second, in most cases examined

[redacted]

TABLE A-4

TYPES AND VALIDITY OF ST. LOUIS DAMAGE CLAIMS INVESTIGATED

Type of Damage	Total Investigations No.	Total Investigations %[b]	Investigated by Contract Engineer No.	Investigated by Contract Engineer %[b]	Validity[a] Doubtful No.	Validity[a] Doubtful %	Validity[a] Probable or Possible No.	Validity[a] Probable or Possible %
Plaster	64	38.8	34	40.3	28	49.1	6	22.2
Plaster and glass			6	9.8	3	5.3	3	11.2
Plaster and furnishings			1	1.2	1	1.8	0	
Glass	68	41.2	25	29.7	15	26.3	10	37.0
Tiles and fixtures	8	4.8	4	4.8	2	3.5	2	7.4
Bric-a-brac	25	15.1	5	6.0	0		5	18.5
Appliances	7	4.2	4	4.8	4	7.0	0	
Structural	21	12.7	5	6.0	4	7.0	1	3.7
Miscellaneous	3	1.8						
	196[c]		84		57	100.0	27	100.0

a. Similar breakdown for claims investigated by USAF personnel not available.
b. Percentages based on 165 claims, see footnote c.
c. Several claims were for more than one type of damage.

[redacted]

many other causes could have produced the same effects. In fact, it was not possible to ascertain the coincidence of boom and damage except through the property occupant's unscientific advice. As a result, the St. Louis test reports were of only limited value, and served mainly to establish outer limits for damage effects at overpressure levels to 3.0 psf.[26]

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APPENDIX B

THE OKLAHOMA CITY TEST PROGRAM

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APPENDIX B

THE OKLAHOMA CITY TEST PROGRAM

B. 1 BOOM SCHEDULES

One objective of the Oklahoma City test program was to understand the causal connection between boom and structural response. This was to be done through extensive instrumentation of several test houses which then would be subjected to a spectrum of boom intensities. In addition, the investigation of any damages claimed by property owners would offer further basis for evaluating structural responses.

A standard flight track was established that would cross an extensively instrumented house in the northwest section of Oklahoma City on a magnetic heading of 051 deg. As indicated in Figure B-1 this placed the bulk of the city to the south of the flight track with the business center about six miles distant. The area to the north of the flight track was predominantly rural.

For the 26 weeks of testing, 1,428 booms were scheduled, 28 during the first week and eight per day thereafter. A few flights were scheduled at other headings (231 deg–the opposite direction along the standard flight path, 130 deg, 310 deg, 170 deg, and 350 deg) in order to permit analyses of alternate pressure distributions, angles of incidence, and response experience. Table B-1 shows the monthly distribution and headings of the 1,253 flights actually made.

The aircraft used in the test had the major characteristics shown in Table B-2. The use of different aircraft permits examination of the variation in responses resulting from shock waves produced by aircraft of differing size and weight. Extrapolation to SST responses is then possible.

The boom levels planned were tied to the limiting figures established in the FAA Request for SST Proposals issued to the participating aircraft manufacturers. These are 2.0 psf during transonic acceleration and 1.5 psf during cruise. Boom intensities were scheduled on a day-to-day basis, as shown in Table B-3.

To attain the desired overpressure at the ground track, it was necessary to fix the altitude and speed for each aircraft. A variety of theoretical formulae and curves based on flight tests has been developed for this purpose. Using these methods, it is possible, for a given airplane in straight, level, and constant-speed flight, to calculate the "nominal" overpressure at the flight track and the lateral

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APPENDIX C

HOUSE 1 STRAIN MEASUREMENT TABLES

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APPENDIX C

HOUSE 1 STRAIN MEASUREMENTS TABLES

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TABLE C-1

HOUSE 1 STRAIN-GAUGE LOCATIONS

Gauge No.	Location	Orientation
1	Center of fixed glass panel 3 ft by 6 ft 10 in. of exterior door in living room.	Horizontal, on inside.
2	Center of wall plate at top of exterior wall on W side of (living room) house.	Horizontal, on edge.
3	Center of stud on N side (exterior wall) of den, E side of window.	Vertical, on inside edge.
4	Center of interior wall stud on E side of living room, stud located approximately center of wall N and S.	Vertical, on inside edge.
5	Center of stud on N exterior wall of bedroom (NE corner of house), stud located approximately center of wall E and W.	Vertical, on inside edge.
6	Center of stud on W side of living room exterior wall facing West directly below roof ridge.	Vertical, on inside edge.
7	Center of interior wall stud on S side of living room, stud located approximately center of wall E and W.	Vertical, on inside edge.
8	Center of rafter on N roof slope, rafter located approximately center of house E and W.	Parallel to rafter, on bottom.
9	Center of rafter on N roof slope, rafter located approximately center of house E and W.	Parallel to rafter, on side centered between top and bottom.
10	Center of rafter on S roof slope over garage, rafter located approximately center of garage E and W.	Parallel to rafter, on bottom.
11	Center of ceiling joist in bedroom NE corner of house, joist located approximately center of room E and W.	Horizontal, on bottom.
12	Roof ridge on main N roof, located approximately one-quarter of house length from E end.	Horizontal, on bottom.
13	Center of stud (exterior wall) on E side of bedroom SE corner of house, stud located approximately center of wall N and S.	Vertical, on inside edge.
14	Center of ceiling joist in living room, joist located approximately center of room E and W.	Horizontal, on bottom.
15	Center of ceiling joist in garage, joist located approximately center of room E and W.	Horizontal, on bottom.

[redacted]

TABLE C-2

OVERPRESSURES AND STRAINS MEASURED DURING SELECTED F-104 FLIGHTS[a]

Flight No.	Overpressures, psf				Pos. Impulse, lb-sec/ft²	Duration of Pos. Portion of N-wave, sec	Wave Shape[b]	Strains, 10^{-6} in./in.							
	Sched-uled	Nom-inal	Out-side	In-side				4[c] Stud, Int.	5 Stud, Ext.-N	6 Stud, Ext.-W	7 Stud, Int.	8 Rafter	10 Rafter Garage	14 Ceiling Joist	15 Ceiling Joist, Garage
7/259	1.5	1.40	2.24	0.50	0.026	0.038	P	13.73	6.90	6.85	3.68	5.34	21.42	10.52	12.82
5/286	1.5	1.55	1.59	0.66	0.032	0.050	NP	24.70	9.66	7.61	8.04	8.30	19.00	10.52	13.07
6/287	1.5	1.55	1.46	0.68	0.026	0.039	NP	25.49	9.41	6.64	6.43	6.22	19.22	11.54	13.07
8/399	1.5	1.52	2.26	-	0.037	0.040	P	20.01	6.67	10.12	9.66	10.58	21.05	12.42	15.87
8/415	1.5	1.50	1.71	-	0.018	0.040	NP	13.97	7.48	7.02	5.41	5.18	18.29	11.16	28.98
1/416	1.5	1.48	1.09	-	0.023	0.041	NR	9.18	3.28	4.04	2.15	4.04	19.44	3.75	10.50
3/418	1.5	1.48	1.27	-	0.026	0.044	NR	12.77	6.90	9.39	5.15	4.98	20.97	11.38	13.00
5/420	1.5	1.48	1.23	0.73	0.026	0.044	NR	12.10	7.88	6.41	5.66	6.06	20.31	9.50	15.00
6/468	1.5	1.48	1.71	-	0.033	0.045	NP	18.63	12.65	12.54	5.87	9.20	26.22	15.01	-
4/486	1.5	1.48	1.77	-	0.024	0.040	P	9.66	8.74	9.89	4.37	8.63	25.88	10.01	12.76
5/516	1.5	1.48	1.82	-	0.023	0.043	NP	15.87	4.14	8.74	4.83	5.98	21.74	9.49	13.11
6/553	1.5	1.48	1.80	-	0.025	0.043	P	13.98	10.27	-	10.74	5.62	24.17	15.30	13.07
8/577	1.5	1.48	2.22	-	0.035	0.040	P	26.88	14.19	-	12.53	12.29	31.64	18.91	20.98
2/602	2.0	1.72	1.71	-	0.022	0.030	NP	14.78	8.48	12.03	6.39	7.22	24.58	11.91	14.60
5/613	2.0	1.72	2.19	-	0.028	0.049	P	10.67	5.01	6.30	3.43	3.94	23.23	7.61	10.96
5/628	2.0	2.04	3.31	-	-	-	-	13.44	9.93	13.80	14.76	7.17	22.56	14.60	13.42
6/629	2.0	1.94	1.93	-	0.029	0.029	NP	12.99	6.06	6.90	6.35	5.54	30.97	10.32	14.24
2/631	2.0	1.33	1.04	-	0.029	0.045	N	8.96	6.32	7.04	3.69	6.12	17.36	8.77	13.01
6/635	2.0	1.42	1.93	-	0.025	0.042	R	11.20	3.41	5.01	1.76	4.35	16.06	11.11	8.48
2/639	2.0	1.38	1.32	-	0.025	0.041	N	11.79	8.48	8.16	3.32	5.41	18.88	13.29	13.59
Averages:		1.55	1.76	-	0.027	0.041		15.04	7.79	8.25	6.21	6.61	22.15	11.36	13.69

[a] Maximum values for flights tabulated are underscored. Stress induced in psi is approximately 1.6 x strain values tabulated, e.g., the maximum increment of stress in the above observations was 31.64 x 1.6 = 51 psi.

[b] N = N-wave shape; P = peaked wave with very short rise time at initial peak; R = rounded, sine-wave appearance; C = peaked wave, long rise time.

[c] Gauge numbers.

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TABLE C-3

OVERPRESSURES AND STRAINS MEASURED DURING B-58 FLIGHTS[a]

Flight No.	Alt., 10^3 ft	Mach	Overpressures, psf: Scheduled	Overpressures, psf: Nominal	Overpressures, psf: Outside	Overpressures, psf: Inside	Pos. Impulse, lb-sec/ft^2	Duration of Pos. Portion of N-wave, sec	Wave Shape[b]	Strains, 10^{-6} in./in.: 4 Stud, Int.	5 Stud, Ext.-N	6 Stud, Ext.-W	7 Stud, Int.	8 Rafter (North)	10 Rafter (South)	14 Ceiling Joist	15 Ceiling Joist Garage
4/314	49.9	2.0	1.5	1.6	1.69	1.12	-	-	-	11.80	10.03	10.09	6.77	7.00	29.32	10.38	-
1/327	50.0	1.9	1.5	1.6	1.34	1.10	-	-	NR	11.72	5.46	9.20	6.86	7.23	17.47	12.29	20.48
4/335	49.9	1.9	1.5	1.6	2.39	-	-	-	NP	17.25	6.86	10.27	8.76	11.04	25.33	16.37[c]	33.20[c]
4/343	49.9	1.9	1.5	1.6	1.46	-	-	-	NR	8.79	4.88	8.72	5.83	5.14	20.65	11.13	22.31[c]
4/748[d]	49.9	2.0	1.5	1.6	1.24	1.70[d]	0.077	0.106	NR	19.55	3.82	6.48	6.73	8.52	23.87	8.06	10.27
4/756	49.9	1.5	1.5	1.5	1.44	1.70	0.074	0.093	N	12.03	3.65	11.91	6.06	10.14	17.25	13.65	18.06
4/764[d]	49.9	2.0	1.5	1.6	1.24	1.59[d]	0.071	0.110	N	21.20	4.10	7.35	7.21	8.11	20.40	8.56	15.02
4/772	49.9	1.9	1.5	1.6	1.46	1.26	0.075	0.101	N	10.82	6.39	10.01	5.80	10.81	18.78	9.41	20.42
4/953	43.0	1.9	2.0	1.8	1.68	1.41	0.071	0.090	-	-	5.20	14.71	5.90	10.14	24.52	18.89	16.57
4/1018	49.9	2.0	2.0	1.6	1.87	-	0.112	0.094	-	17.25	4.82	8.63	6.12	12.40	25.77	12.02	22.73
4/1058	49.9	2.0	2.0	1.6	1.92	-	0.088	0.099	-	13.75	5.00	10.16	8.40	9.46	22.15	14.46	15.68
4/1090	49.9	2.0	2.0	1.6	1.95	-	0.088	0.102	-	-	5.20	10.43	6.35	8.92	24.09	14.10	19.83
Averages:			1.7	1.6	1.64	1.41	0.082	0.099		14.42	5.45	9.84	6.73	9.07	22.42	12.45	19.52
Natural frequency, cps (measured for No. 4/314)										18.2	25.0	-	17.5	28.6	10.9	11.1	5.1

[a] Maximum value at each gauge underscored. Stress induced in psi is approximately 1.6 x strain values tabulated, e.g., the maximum increment of stress in the above observations was 33.20 x 1.6 = 53 psi.

[b] N = N-wave shape; P = peaked wave with very short rise time at initial peak; R = rounded, sine-wave appearance.

[c] Estimated.

[d] Doors and windows open.

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TABLE C-4

OVERPRESSURES AND STRAINS MEASURED DURING THREE F-106 FLIGHTS[a]

Flight No²	Overpressures, psf: Scheduled	Overpressures, psf: Nominal	Overpressures, psf: Outside	Overpressures, psf: Inside	Pos. Impulse, lb-sec/ft²	Duration of Pos. Portion of N-wave, sec	Strains, 10^{-6} in./in.: 4 Stud, Int.	5 Stud, Ext.-N	6 Stud, Ext.-W	7 Stud, Int.	8 Rafter	10 Rafter, Garage	14 Ceiling Joist	15 Ceiling Joist, Garage
1/875	-	1.5	0.98	0.75	0.027	0.058	8.93	6.60	9.12	5.25	9.84	17.79	11.34	13.39
2/876	-	1.6	1.07	0.70	0.030	0.055	11.10	6.84	5.02	5.16	11.90	24.43	11.34	13.39
5/879	-	1.7	1.09	0.92	0.032	0.062	9.89	4.35	10.71	6.26	10.77	20.36	12.07	13.65
Averages:		1.6	1.05	0.79	0.030	0.058	9.96	5.93	8.29	5.56	10.83	21.19	11.58	13.48

[a]Maximum values for flights tabulated are underscored. Stress induced in psi is approximately 1.6 x strain values tabulated; e.g., the maximum increment of stress in the above observations was 24.43 x 1.6 = 39 psi.

[redacted]

TABLE C-5

OVERPRESSURES AND STRAINS MEASURED DURING SELECTED F-101 FLIGHTS[a]

Flight No.	Alt., 10^3ft	Mach	Overpressures, psf				Pos. Impulse, lb-sec/ft^2	Duration of Pos. Portion of N-wave, sec	Wave Shape[b]	Strains at Selected Gauges, 10^{-6} in./in.							
			Sched-uled	Nom-inal	Out-side	In-side				4 Stud, Int.	5 Stud, Ext.-N	6 Stud, Ext.-W	7 Stud, Int.	8 Rafter (North)	10 Rafter (South)	14 Ceiling Joist	15 Ceiling Joist, Garage
3/701	46	1.4	1.2	1.08	1.20	-	0.055	0.083	NR	13.80	4.93	9.88	3.81	4.56	19.10	17.00	20.44
4/710	46	1.5	1.2	1.13	1.56	-	0.046	0.071	N	15.33	3.16	9.20	4.99	4.90	20.53	11.85	19.56
8/714	46	1.5	1.2	1.13	1.22	-	0.040	0.079	N	12.18	3.51	7.31	3.17	4.68	14.10	9.27	11.95
1/745	44	1.5	1.5	1.20	1.22	-	0.054	0.084	N	12.46	8.43	7.40	4.77	5.14	21.70	9.50	20.55
3/747	44	1.5	1.5	1.20	1.29	-	0.051	0.074	N	31.60	6.27	10.05	8.18	8.79	26.04	10.50	19.44
3/831	28	1.45	2.0	2.15	1.69	1.74	0.068	0.076	-	15.33	7.59	10.82	5.23	9.32	25.33	9.34	26.22
4/832	28	1.5	2.0	2.17	2.15	1.57	0.063	0.074	-	16.24	6.87	11.37	5.57	2.60	24.24	9.96	25.94
2/838	34	1.46	2.0	1.69	1.43	1.24	0.053	0.080	-	8.96	5.55	8.79	4.12	4.73	15.94	8.63	15.43
4/840	34	1.46	2.0	1.69	2.67	0.85	0.061	0.076	-	9.86	4.60	7.58	5.06	6.08	22.06	11.24	21.88
3/847	34	1.43	2.0	1.67	2.74	1.20	0.061	0.073	-	15.23	5.19	11.77	5.96	8.86	30.36	13.91	30.36
1/1103	33	1.42	2.0	1.73	1.81	-	0.067	0.068	NR	-	4.79	9.45	7.27	7.96	24.46	13.65	29.77
7/1117	35	1.42	2.0	1.60	2.48	-	0.063	0.066	P	15.36	3.89	10.84	7.35	7.98	23.07	12.71	23.72
6/1124	35	1.45	2.0	1.62	2.79	-	0.056	0.066	P	14.25	6.10	12.42	26.04	10.00	20.27	13.91	19.71
7/1133	37	1.45	2.0	1.50	3.34	-	0.073	0.076	P	12.84	5.98	6.89	7.08	6.69	24.58	11.67	29.02
6/1140	35	1.42	2.0	1.60	2.43	-	0.066	0.080	P	21.35	7.35	14.64	11.50	10.92	23.81	12.84	24.68
6/1148	35	1.5	2.0	1.65	2.42	-	0.074	0.073	P	30.50	8.70	18.95	14.85	14.06	29.97	16.00	27.01
5/1155	35	1.42	2.0	1.60	2.46	-	0.069	0.070	NP	19.75	7.77	12.42	8.16	9.73	29.66	13.95	27.49
5/1163	35	1.5	2.0	1.65	3.15	-	0.071	0.072	P	20.40	6.86	12.29	8.77	10.00	35.14	13.25	23.53
8/1174	41	1.6	1.3	1.37	2.45	-	0.052	0.069	P	13.70	4.12	7.98	5.34	6.51	18.02	13.19	14.82
1/1183	40	1.42	1.3	1.32	1.52	-	0.064	0.077	NR	15.50	5.13	9.82	5.53	8.90	21.78	11.83	20.91
5/1195	43	1.35	1.3	1.15	1.32	-	0.050	0.111	C	11.85	3.94	9.93	4.61	5.85	19.22	11.58	19.08
8/1206	45	1.48	1.3	1.16	1.08	-	0.022	0.064	NP	16.10	5.43	8.82	5.53	9.92	27.10	11.16	22.64
5/1219	35	1.42	2.0	1.60	1.09	-	0.034	0.080	NR	12.70	4.09	9.38	6.67	8.11	25.83	12.36	17.73
8/1230	41	1.46	1.3	1.30	1.20	-	0.039	0.066	NR	13.21	5.37	8.95	6.76	9.92	22.44	13.04	15.33
5/1235	41	1.42	1.3	1.28	2.36	-	0.037	0.065	P	19.33	4.14	8.34	6.07	9.86	18.30	11.56	17.60
5/1243	41	1.47	1.3	1.22	1.32	0.95	0.035	0.065	NP	16.39	4.83	7.32	6.88	8.59	20.45	8.82	20.41
6/1251	43	1.5	1.3	1.24	1.62	-	0.049	0.068	N	19.22	3.84	7.28	6.11	9.10	19.69	9.86	18.95
Averages:			1.7	1.40	1.93	-	0.055	0.074	-	16.29	5.50	10.07	7.24	7.91	23.08	11.94	21.60

[a] Maximum values for flights tabulated are underscored. Stress induced in psi is approximately 1.6 x strain values tabulated, e.g., the maximum increment of stress in the above observations was 35.14 x 1.6 = 56 psi.

[b] N = N-wave shape; P = peaked wave with very short rise time at initial peak; R = rounded, sine-wave appearance; C = peaked wave, long rise time.

TA:LE C-6

SELECTED GROUPS OF F-101 FLIGHTS INVOLVING RELATED OVERPRESSURE VALUES[a]

Flight No.	Alt., 10^3ft.	Mach	Overpressures, psf: Sched-uled	Overpressures, psf: Nom-inal	Overpressures, psf: Out-side	Overpressures, psf: In-side	Pos. Impulse, lb-sec/ft^2	Duration of Pos. Portion of N-wave, sec	Wave Shape[b]	Strains, 10^{-6} in./in.: 4 Stud, Int.	5 Stud, Ext.-N	6 Stud, Ext.-W	7 Stud, Int.	8 Rafter (North)	10 Rafter (South)	14 Ceiling Joist	15 Ceiling Joist, Garage
Flights with overpressure near a nominal value of 1.80 psf:																	
5/827	34	1.5	1.5	1.78	1.79	1.10	0.076	0.081	--	11.73	5.75	12.18	6.13	8.43	24.90	13.85	29.26
1/861	33	1.48	1.5	1.84	1.82	1.24	0.053	0.070	--	--	8.21	9.20	5.50	7.97	25.46	7.87	29.19
1/942	33	1.41	2.0	1.80	1.82	1.28	0.054	0.065	--	--	8.25	10.43	6.41	9.26	30.18	11.67	22.45
1/993	33	1.35	2.0	1.75	1.86	1.32	0.062	0.080	--	--	5.04	10.96	5.75	7.20	26.13	16.13	19.94
1/1103	33	1.42	2.0	1.80	1.81	--	0.067	0.068	NR	--	4.79	9.45	7.27	7.96	24.46	13.65	29.77
Averages:			1.8	1.79	1.82	1.23	0.062	0.073	--	11.73	6.41	10.44	6.21	8.16	26.23	12.63	26.12
Flights at nominal Δp approx. 1.82, actual approx. 2.20:																	
1/869	33	1.46	2.0	1.83	2.20	1.37	0.055	0.064	--	17.02	6.04	9.42	8.11	11.29	26.27	12.07	20.59
7/881	33	1.48	2.0	1.84	2.18	1.28	0.058	0.067	--	15.68	10.33	11.10	6.51	8.11	32.57	14.48	36.05
2/943	33	1.42	2.0	1.80	2.25	1.36	0.059	0.074	--	--	8.88	10.16	6.41	9.79	22.21	13.70	21.36
6/1005	33	1.45	2.0	1.82	2.20	--	0.075	0.067	--	--	6.89	16.18	8.15	9.06	47.43	23.67	35.32
Averages:			2.0	1.82	2.21	1.34	0.062	0.068	--	16.35	8.04	11.72	7.30	9.56	32.12	15.98	28.33
Flights at nominal Δp approx. 1.77, actual approx. 2.65:																	
4/840	34	1.46	2.0	1.76	2.67	0.085	0.061	0.076	--	9.86	4.60	7.58	5.06	6.08	22.06	11.24	21.88
1/1071	33	1.4	2.0	1.78	2.62	--	0.068	0.074	--	--	5.30	14.17	10.61	9.84	22.42	15.71	22.18
Averages:			2.0	1.77	2.65	0.085	0.065	0.075	--	9.86	5.45	10.89	7.84	7.96	22.24	13.48	22.03
Flights with peaked pressure wave, Δp approx. 1.85, and lower nominal values:																	
5/727	44	1.5	1.2	1.23	1.97	1.07	0.0537	0.083	NP	21.50	4.27	9.76	6.35	9.53	20.09	11.96	21.36
5/780	44	1.48	1.5	1.23	1.80	0.95	0.0522	0.085	C	12.85	5.52	9.47	5.88	11.22	21.53	8.63	18.75
6/798	44	1.5	1.5	1.23	1.81	0.98	0.052	0.060	--	9.99	5.03	8.90	5.88	8.49	20.21	10.04	21.36
2/808	42	1.5	1.5	1.31	1.82	1.19	0.061	0.070	--	10.67	6.66	9.58	4.36	7.58	23.30	10.61	23.99
3/809	42	1.5	1.5	1.31	1.91	0.94	0.062	0.069	--	14.30	5.63	11.36	5.57	11.44	24.86	9.55	26.20
Averages:			1.4	1.26	1.86	1.03	0.056	0.073	--	13.86	5.42	9.81	5.61	9.65	22.00	10.16	22.33

[a] Maximum values are underscored.

[b] N = N-wave shape; P = peaked wave with very short rise time at initial peak; R = rounded, sine-wave appearance; C = peaked wave, long rise time.

[redacted]

TABLE C-7

FLIGHTS WITH OVERPRESSURES EXCEEDING 3.0 PSF[a]

Flight No.	Aircraft	Alt., 10^3 ft.	Mach	Overpressures, psf				Pos. Impulse, lb-sec/ft^2	Duration of Pos. Portion of N-wave, sec	Wave Shape[b]	Strains, 10^{-6} in./in.							
				Sched-uled	Nom-inal	Out-side	In-side				4 Stud, Int.	5 Stud, Ext.-N	6 Stud, Ext.-W	7 Stud, Int.	8 Rafter (North)	10 Rafter (South)	14 Ceiling Joist	15 Ceiling Joist, Garage
5/628	F-104	21	1.4	2.0	2.04	3.31	--	--	--	--	13.44	9.93	13.80	14.76	7.17	22.56	14.60	13.42
3/693	F-101	40	1.4	2.0	1.35	3.24	--	--	--	--	17.94	3.14	9.86	6.10	4.86	18.36	9.75	19.75
8/970	F-101	37	1.44	2.0	1.55	3.08	1.18	0.073	0.069	--	--	5.19	13.10	6.01	9.73	30.08	9.82	26.56
7/1133	F-101	37	1.45	2.0	1.55	3.34	--	0.073	0.076	P	12.84	5.98	8.89	7.08	6.69	24.58	11.67	29.02
5/1163	F-101	35	1.5	2.0	1.70	3.15	--	0.071	0.072	P	20.40	6.86	12.29	8.77	10.00	35.14	13.25	23.53
	Averages:				1.64	3.22	--	.072	.072		16.16	6.22	11.59	8.54	7.69	26.14	11.82	22.46

[a]Strain data for other flights were not available. Maximum values for flights tabulated are underscored.

[b]P = peaked wave with very short rise time at initial peak.

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[redacted]

TABLE C-8

DAILY PEAK OVERPRESSURE FLIGHTS, WEEK ENDING JULY 19[a]

Flight No.	Alt., 10^3 ft.	Mach	Overpressures, psf				Pos. Impulse, lb-sec/ft^2	Duration of Pos. Portion of N-wave, sec	Wave Shape[b]	Strains, 10^{-6} in./in.							
			Sched-uled	Nom-inal	Out-side	In-side				4 Stud, Int.	5 Stud, Ext.-N	6 Stud, Ext.-W	7 Stud, Int.	8 Rafter (North)	10 Rafter (South)	14 Ceiling Joist	15 Ceiling Joist, Garage
7/1117	35	1.42	2.0	1.65	2.48	-	0.0632	0.066	P	15.36	3.89	10.84	7.35	7.98	23.07	12.71	23.72
6/1124	35	1.45	2.0	1.67	2.79	-	0.0556	0.066	P	14.25	6.10	12.42	26.04	10.00	20.27	13.91	19.71
7/1133	37	1.45	2.0	1.55	3.34	-	0.0733	0.076	P	12.84	5.98	8.89	7.08	6.69	24.58	11.67	29.02
6/1140	35	1.42	2.0	1.65	2.43	-	0.0655	0.080	P	21.35	7.35	14.64	11.50	10.82	23.81	12.84	24.68
6/1148	35	1.50	2.0	1.70	2.42	-	0.0743	0.073	P	30.50	8.70	18.95	14.85	14.06	29.97	16.00	27.01
5/1155	35	1.50	2.0	1.70	2.46	-	0.0688	0.070	NP	19.75	7.77	12.42	8.16	9.73	29.66	13.95	27.49
5/1163	35	1.50	2.0	1.70	3.15	-	0.0709	0.072	P	20.40	6.86	12.29	8.77	10.90	35.14	13.25	23.53
Averages:			2.0	1.66	2.72		0.0674	0.072		19.21	6.66	12.92	11.96	9.90	26.64	13.48	25.04

[a] Average overpressure for all flights during each week was the highest (1.80 psf) for this week. Coincidentally, strain data were provided for each daily flight with peak overpressure at House 1. Maximum values for flights tabulated are underscored.

[b] N = N-wave shape; P = peaked wave with very short rise time at initial peak.

[redacted]

[redacted]

TABLE C-9

REVERSE COURSE (F-104) FLIGHTS, FEBRUARY 19-20[a]

Flight No.[b]	Overpressures, psf: Scheduled	Nominal	Outside	Inside	Pos. Impulse, lb-sec/ft^2	Duration of Pos. Portion of N-wave, sec	Wave[c] Shape	Strains, 10^{-6} in./in.: 4 Stud, Int.	5 Stud, Ext.-N	6 Stud, Ext.-W	7 Stud, Int.	8 Rafter (North)	10 Rafter (South)	14 Ceiling Joist	15 Ceiling Joist, Garage
1/93	1.5	1.10	0.56	0.19	0.0162	0.064	--	2.04	1.70	1.68	1.65	1.99	5.29	6.93	5.51
2/94	1.5	1.10	1.11	0.29	0.0271	0.052	NR	7.37	4.05	3.20	4.49	4.94	10.37	12.90	10.40
3/95	1.5	1.24	1.03	0.28	0.0252	0.049	NR	6.46	4.69	3.60	3.94	4.72	10.16	9.77	9.30
4/96	1.5	1.24	1.18	0.31	0.0314	0.0455	NR	7.71	5.91	3.60	5.04	6.41	11.43	12.30	10.71
5/97	1.5	1.30	1.18	0.24	0.0306	0.051	NR	1.25	3.24	3.76	0.63	4.57	7.62	1.57	31.19
6/98	1.5	1.30	1.65	0.33	0.0311	0.05	P	12.02	6.07	4.87	5.99	7.66	10.58	15.67	11.82
7/99	1.5	1.24	1.22	0.34	0.0352	0.0505	NP	10.66	5.42	4.79	5.75	6.12	11.64	15.68	12.05
2/101	1.5	1.24	1.00	0.27	0.0276	0.05	NR	8.79	5.99	3.88	5.95	5.71	11.86	14.47	11.98
Averages:		1.22	1.12	0.28	0.0281	0.0515		7.04	4.63	3.67	4.18	5.27	9.87	11.05	12.87

[a] Maximum values for flights tabulated are underscored. Stress induced in psi is approximately 1.6 x strain values tabulated; e.g., the maximum increment of stress in the above observations was 31.19 x 1.6 = 0 psi.

[b] Strain data for 8 of 14 reverse flights were provided for this study.

[c] N = N-wave shape; P = peaked wave with very short rise time at initial peak; R = rounded, sine-wave appearance.

[redacted]

[redacted]

TABLE C-10

OTHER NON-STANDARD (F-104) FLIGHTS[a]

Flight No.	Overpressures, psf Sched-uled	Nom-inal	Out-side	Pos. Impulse, lb-sec/ft2	Duration of Pos. Portion of N-wave, sec	Wave Shape[b]	Strains, 10^{-6} in./in. 4 Stud. Int.	5 Stud. Ext.-N	6 Stud. Ext.-W	7 Stud, Int.	8 Rafter (North)	10 Rafter, Garage (South)	14 Ceiling Joist	15 Ceiling Joist Garage
Aircraft heading 310° (28 April)														
1/556	1.5	1.48	1.29	0.0295	0.0485	NP	9.18	5.99	--	4.98	5.22	23.81	--	12.63
2/557	1.5	1.48	1.37	0.0246	0.0485	NP	9.63	5.75	--	6.69	5.98	22.71	14.49	11.22
3/558	1.5	1.48	0.75	0.0249	0.059	R	8.74	1.47	--	3.35	3.60	19.44	--	10.66
4/559	1.5	1.48	1.71	0.0344	0.057	P	13.89	4.28	--	5.32	7.13	25.99	--	16.55
Avg.	1.5	1.48	1.28	0.0283	0.0532		10.36	4.37		5.08	5.48	22.98		12.76
Aircraft heading 130° (28 April)														
5/560	1.5	1.48	0.72	0.0181	0.0535	R	9.41	6.73	--	5.83	5.91	11.14	6.45	10.94
6/561	1.5	1.48	1.29	0.0297	0.0435	NP	15.90	10.88	--	5.75	6.37	22.06	10.40	13.74
7/562	1.5	1.48	1.01	0.0214	0.0475	C	9.63	8.32	--	4.98	5.68	8.52	6.99	8.70
8/563	1.5	1.48	0.72	0.0177	0.0785	R	6.27	4.04	--	4.20	4.91	6.55	3.95	7.01
Avg.	1.5	1.48	0.93	0.0217	0.0582		10.30	7.49		5.19	5.71	12.06	6.94	10.09
Aircraft heading 170° (29 April)														
1/564	1.5	1.22	1.22	0.0265	0.0425	NP	12.91	9.78	--	5.75	8.23	13.40	9.86	11.96
2/565	1.5	0.94	1.07	0.0247	0.042	NP	9.13	8.44	--	5.15	7.54	12.30	9.60	11.13
3/566	1.5	0.94	0.77	0.0201	0.0485	NR	10.68	7.70	--	4.38	5.87	12.30	7.80	10.85
4/567	1.5	0.94	0.64	0.0189	0.0465	R	10.68	7.22	--	3.95	4.95	10.33	7.26	9.18
Avg.	1.5	1.01	0.92	0.0225	0.0448		10.85	8.28		4.80	6.64	12.08	8.63	10.78
Aircraft heading 350° (29 April)														
5/568	1.5	1.48	2.00	0.0261	0.044	P	12.69	4.52	--	4.98	5.33	26.36	19.20	12.52
6/569	1.5	1.48	1.56	0.0277	0.0455	P	17.59	6.48	--	4.29	6.10	54.05[c]	22.33	15.02
Avg.	1.5	1.48	1.78	0.0269	0.0447		15.14	5.50		4.63	5.71	40.20	20.76	13.77

[a] Maximum values for flights tabulated are underscored. Stress induced in psi is approximately 1.6 x strain values tabulated; e.g., the maximum increment of stress in the above observations was 54.05 x 1.6 = 87 psi.

[b] N = N-wave shape; P = peaked wave with very short rise time at initial peak; R = rounded, sine-wave appearance; C = peaked wave, long rise time.

[c] Reported as questionable.

[redacted]

TABLE C-11

OVERPRESSURES AND STRAINS FOR DIFFERENT MACH ANGLES[a]

Flight No.	Alt. 10^3 ft	Mach	Overpressures, psf: Scheduled	Overpressures, psf: Nominal	Overpressures, psf: Outside	Overpressures, psf: Inside	Pos. Impulse, lb-sec/ft^2	Duration of Pos. Portion of N-wave, sec	Wave Shape[b]	Strains, 10^{-6} in./in.: 4 Stud. Int.	5 Stud. Ext.-N	3 Stud. Ext.-W	7 Stud. Int.	8 Rafter (North)	10 Rafter (South)	14 Ceiling Joist	15 Ceiling Joist, Garage
B-58 Flights at Mach 2.0 (30.0°)																	
4/314	49.9	2.00	1.5	1.6	1.69	1.12	-	-	-	11.80	10.03	10.09	6.77	7.00	29.32	10.38	-
4/748[c]	49.9	2.00	1.5	1.6	1.24	1.70[c]	0.077	0.106	NR	19.55	3.82	6.48	6.73	8.52	23.87	8.06	10.27
4/764[c]	49.9	2.00	1.5	1.6	1.24	1.59[c]	0.071	0.110	N	21.20	4.10	7.35	7.21	8.11	20.40	8.56	15.02
4/1018	49.9	2.00	2.0	1.6	1.87	-	0.112	0.094	-	17.25	4.82	8.63	6.12	12.40	25.77	12.02	22.73
4/1058	49.9	2.00	2.0	1.6	1.92	-	0.088	0.099	-	13.75	5.00	10.16	8.40	9.46	22.15	14.46	15.68
4/1090	49.9	2.00	2.0	1.6	1.95	-	0.088	0.102	-	-	5.20	10.43	6.35	8.92	24.09	14.10	19.83
Averages:			1.8	1.6	1.65	1.47	0.087	0.102		16.71	5.50	8.86	6.83	9.07	24.27	11.26	16.71
F-101 Flights at Mach 1.4 at Altitude > 36,000 ft (45.5°)																	
8/633	38	1.40	2.0	1.45	2.72	-	0.0622	0.082	-	11.27	6.45	12.76	5.40	3.49	20.26	12.55	25.74
7/690	40	1.40	2.0	1.35	1.98	-	0.0547	0.0715	-	22.85	3.34	10.69	5.19	4.76	20.53	8.24	25.94
3/693	40	1.40	2.0	1.35	3.24	-	0.0463	0.0785	-	17.94	3.14	9.86	6.10	4.86	18.36	9.75	19.75
3/701	46	1.40	1.2	1.11	1.20	-	0.0550	0.083	-	13.80	4.93	9.88	3.81	4.56	19.10	17.00	20.44
3/1177	41	1.40	1.3	1.31	1.61	-	0.0586	0.079	NR	12.59	5.59	10.16	5.27	8.02	19.40	12.50	18.58
1/1183	40	1.42	1.3	1.36	1.52	-	0.0640	0.077	NR	15.50	5.13	9.82	5.53	8.90	21.78	11.83	20.91
5/1235	41	1.42	1.3	1.32	2.36	-	0.0370	0.065	P	19.33	4.14	8.34	6.07	9.86	18.30	10.56	17.60
Averages:			1.6	1.32	2.09		0.0540	0.0766		16.18	4.67	10.22	5.34	6.35	19.68	11.78	21.28

[a] Maximum values for each group of flights tabulated are underscored.

[b] N = N-wave shape; P = peaked wave with very short rise time at initial peak; R = rounded, sine-wave appearance.

[c] Doors and windows open.

TABLE C-12

OVERPRESSURES AND STRAINS WITH HOUSE DOORS AND WINDOWS OPEN[a]

Flight No.[b]	Overpressures, psf				Pos. Impulse, lb-sec/ft^2	Duration of Pos. Portion of N-wave, sec	Wave Shape[d]	Strains at Selected Guages, 10^{-6} in./in.							
	Scheduled	Nominal	Outside	Inside[c]				4 Stud, Int.	5 Stud, Ext.-N	6 Stud, Ext.-W	7 Stud, Int.	8 Rafter (North)	10 Rafter, Garage (South)	14 Ceiling Joist	15 Ceiling, Joist Garage
2/312	1.5	1.36	1.18	0.65	--	--	--	14.77	5.63	9.29	5.58	5.11	17.25	12.20	12.88
6/316	1.5	1.42	1.02	0.66	0.0216	0.041	NP	13.30	5.50	6.28	4.40	3.70	16.82	9.50	11.33
8/318	1.5	1.42	1.22	0.71	0.0271	0.042	NR	13.97	5.63	7.17	6.77	4.64	20.91	11.29	13.91
2/320	1.5	1.42	1.34	0.81	0.0259	0.039	NR	17.47	4.28	7.40	6.52	6.08	20.57	--	12.55
4/322	1.5	1.42	1.24	0.79	0.0226	0.037	NP	16.46	3.02	6.59	5.66	4.06	21.90	12.46	10.46
5/323	1.5	1.36	0.80	0.68	0.0235	0.047	R	12.66	2.35	7.66	4.29	4.73	18.14	9.57	12.29
8/326	1.5	1.42	0.84	0.63	0.0240	0.046	R	16.91	4.20	4.99	4.29	5.68	13.71	7.56	13.59
5/428	1.5	1.48	1.76	0.89	0.0333	0.042	NP	33.81	6.10	9.78	10.70	8.74	22.77	22.25	19.32
7/737	1.2	1.16	2.41	--	0.0599	0.077	P	24.06	4.70	12.03	9.09	--	--	11.76	21.93
2/746	1.5	1.23	1.17	--	0.0397	0.080	N	13.57	5.72	6.61	5.71	6.96	18.23	7.50	18.44
8/752	1.5	1.23	1.36	--	0.0366	0.076	NP	19.54	4.93	6.87	6.05	6.22	17.58	7.00	15.80
7/759	1.5	1.23	2.14[e]	--	0.0552	0.074	NP	28.38	6.50	14.07	9.60	13.43	24.77	14.42	22.64
1/761	1.5	1.23	1.38	--	0.0472	0.075	N	19.39	9.69	7.35	6.18	7.17	21.48	10.38	15.86
Averages:	1.5	1.34	1.37		0.0347	0.056		18.79	5.25	8.16	6.53	6.38	19.51	11.32	15.46

[a] Maximum values for flights tabulated are underscored.

[b] Flights through 428 are F-104; remainder are F-101.

[c] Microphone in middle bedroom with one exterior wall facing north. Seven inside pressures averaged 0.70 vs. 1.09 outside, compared with 0.43 vs. 1.10 for the remaining 8 flights the same days with doors and windows closed.

[d] N = N-wave shape; P = peaked wave with very short rise time at initial peak; R = rounded, sine-wave appearance.

[e] NASA report value: 1.14.

[redacted]

TABLE C-13

COMPARISON OF FEBRUARY-MAY-JULY STRAINS[a]

Flight No.	Alt. 10^3ft	Mach	Overpressures, psf: Sched-uled	Nom-inal	Out-side	In-side	Pos. Impulse, lb-sec/ft^2	Duration of Pos. Portion of N-wave, sec	Wave Shape[b]	Strains, 10^{-6} in./in.: 4 Stud. Int.	5 Stud. Ext.-N	6 Stud. Ext.-W	7 Stud. Int.	8 Rafter (North)	10 Rafter (South)	14 Ceiling Joist	15 Ceiling Joist, Garage
February (F-104)																	
3/79	31	1.50	1.5	1.30	1.43	0.36	0.0236	0.044	NP	9.66	4.98	7.06	3.49	3.13	15.15	7.51	10.06
8/138	32	1.50	1.5	1.24	1.52	0.37	0.0305	0.0485	NP	11.42	5.39	10.69	5.12	3.37	23.57	8.87	15.12
7/145	30	1.50	1.5	1.36	1.43	0.47	0.0293	0.0425	NP	14.43	8.91	9.30	5.08	6.35	17.68	9.65	14.75
6/152	30	1.50	1.5	1.36	1.48	0.47	0.0258	0.0435	P	12.51	5.91	8.92	4.76	6.07	22.19	9.65	14.99
4/166	32	1.50	1.5	1.24	1.46	0.43	0.0234	0.039	P	11.76	8.02	10.42	5.39	6.86	16.70	10.40	11.83
Averages:			1.5	1.30	1.46	0.42	0.0265	0.0435		11.96	6.64	9.28	4.77	5.16	19.06	9.22	13.35
May (F-104)																	
1/578	24	1.50	2.0	1.79	1.41	-	0.0266	0.046	N	12.99	10.03	-	4.63	6.25	17.92	14.50	13.10
2/631	30	1.40	2.0	1.33	1.46	-	0.0239	0.0455	N	8.96	6.82	7.04	3.69	6.12	17.36	8.77	13.01
7/655	30	1.70	2.0	1.42	1.40	-	0.0254	0.041	P	11.05	6.25	10.68	4.07	5.89	20.57	10.66	12.59
7/662	30	1.50	2.0	1.36	1.44	-	0.0281	0.048	NR	15.54	4.78	4.13	4.32	7.71	39.84	11.61	13.19
3/674	30	1.65	2.0	1.40	1.64	-	0.0290	0.0425	P	13.17	7.88	6.87	4.70	6.44	18.37	9.48	11.31
Averages:			2.0	1.46	1.45		0.0266	0.0446		12.34	7.15	7.18	4.28	6.48	22.81	11.00	12.64
July (F-101)																	
1/1031	33	1.36	2.0	1.75	1.45	-	0.061	0.082	-	13.00	5.44	9.12	3.79	7.80	23.07	13.39	21.83
3/1033	35	1.42	2.0	1.66	1.45	-	0.071	0.076	-	12.75	5.59	8.99	4.51	6.81	25.44	11.85	18.87
3/1177	41	1.40	1.3	1.31	1.61	-	0.0586	0.079	NR	12.59	5.59	10.16	5.27	8.02	19.40	12.50	18.58
1/1183	40	1.42	1.3	1.36	1.52	-	0.0640	0.077	NR	15.50	5.13	9.82	5.53	8.90	21.78	11.83	20.91
5/1195	43	1.35	1.3	1.20	1.32	-	0.0497	0.111	C	11.85	3.94	9.93	4.61	5.85	19.22	11.58	19.08
Averages:			1.6	1.46	1.47		0.0371	0.085		13.14	5.14	9.60	4.74	7.48	21.78	12.23	19.85

[a] Maximum values for each group of flights tabulated are underscored.

[b] N = N-wave shape; P = peaked wave with very short rise time at initial peak; R = rounded, sine-wave appearance; C = peaked wave, long rise time.

[redacted]

APPENDIX D

REGRESSION ANALYSIS OF OVERPRESSURES, IMPULSES, AND STRAINS

This appendix examines the relationships between overpressure and strain and between impulse and strain. In order to approximate a laboratory test as closely as possible, the measurements for the two instrumented roof rafters in House 1 were used. Both of these rafters received the direct loading imposed by the overpressure wave on the roof section. Other instrumented members received the pressure loading after it was transmitted through some intermediate air space, e.g., that between the brick veneer and a framed wall, between the roof and a ceiling section, or between exterior walls and interior walls.

In addition, the pressure wave diffracts progressively about the house exterior and through its interior, producing a varying interaction of forces of different magnitudes acting in different time sequence and in different directions. For many of the strain gauge locations, the nature of the pressure loading in relation to the measured outside and inside overpressures would be a matter of conjecture. From this point of view the garage roof section facing south (containing the rafter at Gauge 10) furnished, it is believed, the best measurements.

Sufficient sample measurements were available only for the F-104 and F-101. Only three measurements were available for the F-106 and these have not been used. Twelve overpressure measurements were available for the B-58 strain measurements, but only eight impulse values. Because of the significance of the higher impulse values to this analysis, these B-58 measurements were employed.

For a roof rafter acting as a beam, the physical relationship of stress to a uniform static loading would be as follows:

$$\text{Stress} = \frac{My}{I} = \frac{wl^2y}{8I}$$

where M is the bending moment, y the distance from the neutral fiber to the point of measurement, I the moment of inertia, l the length, and w the unit load. For a beam of fixed cross section and length all values but stress and the unit load are constant and the equation reduces to the form $Y = bx$. Under laboratory conditions, dynamic loads could be made to follow the same law.

Under the test conditions in Oklahoma City, there was some variation in individual data points from the $Y = bx$ equation. As Appendix B indicates, there was a sizeable

range of error (15 percent or more) in overpressure measurements. Evidence examined in Section 5.1 above suggests that "spike peak" overpressures produce stresses varying from the $Y = bx$ function. Strain (stress) values could be subject to varying amplification ranging from perhaps 1.6 to 2.0 as is explained in Appendix E. Nevertheless, the linear function best representing the scattered points adequately permits examination of the relationships.

For all normal N-wave overpressures, impulse is the product of overpressure and duration. Since for each aircraft the wave duration is basically constant at a fixed altitude and practically so over the range of test altitudes, the strain-impulse function similarly becomes a linear function of the same form, $Y' = b'x'$, with b' varying for each aircraft. For waveforms other than the normal N-wave, the integration values were obtained by NASA through planimetry and were somewhat scattered about the normal N-wave values.

In order to quantify and compare the relationships between overpressure and strain, and between impulse and strain, straight lines were fitted to the observed data by the method of least squares. This method normally produces an equation of the form $Y_c = a + bx$ where a and b are so derived from the observed data that they minimize the sum of the squares of the vertical deviations of observed points from the resulting regression line (i.e., $\sum (Y_i - Y_c)^2$ is a minimum, where the Y_i's are actual observations and the Y_c's are the points on the regression line).

In this analysis, impulse and overpressure are the independent variables and strain is dependent. As any function representing the relationship between these variables must pass through the origin, this restraint was incorporated into the analysis. Thus, the regression equations derived are of the following form:

$$Y_c \text{ (Strain)} = bx \text{ (Impulse)}$$

$$Y_c \text{ (Strain)} = bx \text{ (Overpressure)} .$$

Figures D-1 and D-2 show the lines and data points for the instrumented garage roof rafter of House 1. Although not included in this report, the same examination was made for measurements at the instrumented house roof rafter with comparable results.

Figure D-1 indicates that the relationship between overpressure and resulting strain does not vary significantly with aircraft type. If this is true, then the impulse required at the same overpressure to produce a given strain should vary from aircraft to aircraft in direct proportion to the length of the wave produced by the aircraft. Table D-1 indicates the relative wavelengths of the three test aircraft and compares these with the relative impulse required to produce a given strain (see Figure D-2).

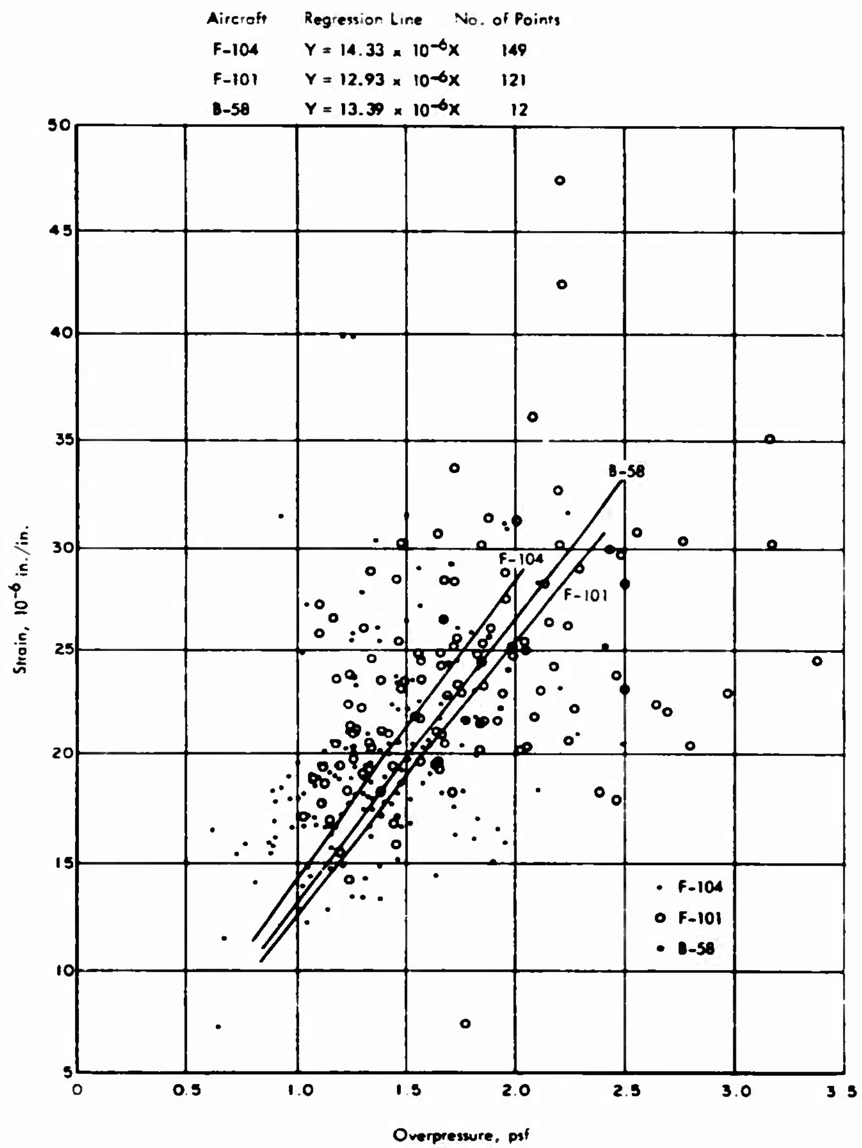

FIGURE D-1 Strains at Bottom Edge of Garage Roof Rafter vs. Overpressures (Gauge No. 10; roof section faces south)

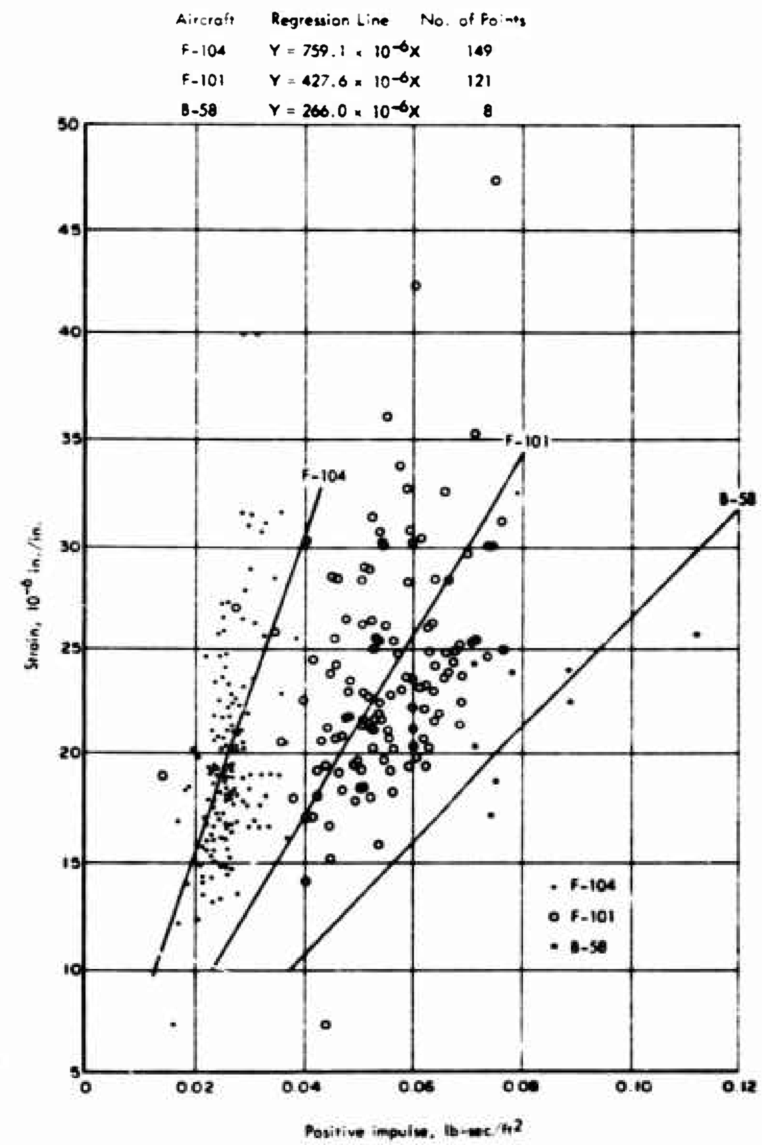

FIGURE D-2 Strains at Bottom Edge of Garage Roof Rafter vs. Impulses (Gauge No. 10; roof section faces south)

[redacted]

TABLE D-1

OVERPRESSURE WAVELENGTH AND IMPULSE REQUIRED TO PRODUCE GIVEN STRAIN: COMPARISON OF THREE AIRCRAFT

	F-104	F-101	B-58
Length of wave, sec	0.08	0.14	0.20
Relative wavelength (= Relative impulse value for same overpressure)	1.0	1.75	2.50
Positive impulse required to produce strain of 30×10^{-6} in./in., lb-sec/ft^2 (See Figure D-2).	0.0398	0.0705	0.1132
Relative positive impulse required to produce strain of 30×10^{-6} in./in.	1.0	1.77	2.84

The relative impulses required to produce a given strain agree closely with the relative wavelengths produced by the three aircraft. Hence, Figure D-2 corroborates the conclusion reached from Figure D-1 that aircraft size does not have an effect on structural response so long as overpressures are the same.

Accordingly, the Oklahoma City structural response test results should be directly applicable to the SST since the tests were conducted at the expected overpressure range of the SST.

[redacted]

APPENDIX E

SOME THEORETICAL ASPECTS OF STRUCTURAL RESPONSE TO SONIC BOOM

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E.1 FREE-STREAM PRESSURE VS. PRESSURE ON STRUCTURES

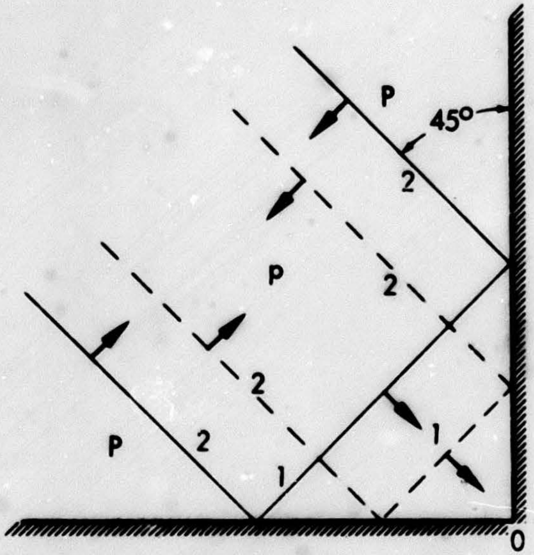
To what overpressures were the test houses and other buildings in Oklahoma City subjected? Research by NASA has shown that overpressure measured at the ground is for practical purposes twice the "free-stream, in air" overpressure because of reflection from the earth's surface. The overpressures cited in this study are ground overpressures.

Although unconfirmed by research, theory suggests that in a reentrant, two-sided corner (see Figure E-1) the pressure on either surface can be double the ground pressure as in Figure E-1 and that in a three-sided reentrant corner the intensity might triple. Although the necessary combination of reentrant corner and angle of incidence may be infrequent, and the distribution of focussed pressures scattered, such a possibility may be one explanation of effects which are unexpectedly greater than the nominal pressure would indicate. Work sponsored by the Atomic Energy Commission has reported this reflection effect for overpressures in the sonic boom range.

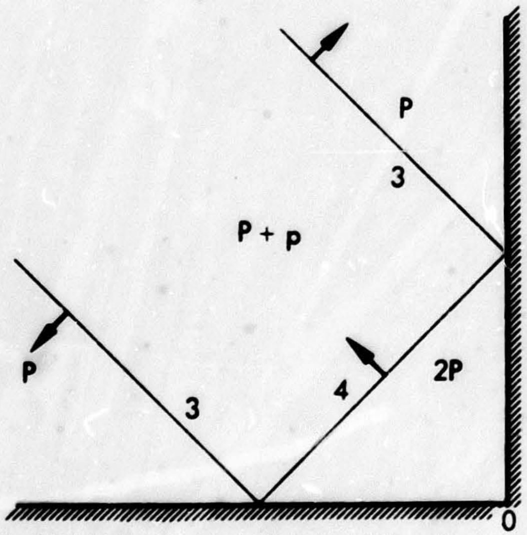
E.2 VIBRATION CONCEPTS

The dynamic pressure loading not only varies as to magnitude but also has the two phases (positive-negative, or push-pull) of the characteristic N-wave. In the near-ideal shape of the N-wave, the positive and negative pressures forming the two halves of the wave are approximately equal and each lasts for about one-half of the total wave duration. The pressure-wave duration varies principally with the type of aircraft; about 0.08 seconds for a small fighter like the F-104, about 0.2 seconds for the B-58, and about 0.4 to 0.5 seconds for the SST.

After the pressure wave passes the structural elements loaded by the overpressure may continue in free vibratory motion until they come to rest. The natural vibratory frequency of a given structural element may be such that after the positive portion of the N-wave passes the motion of the element in returning to rest may be reinforced by the pull action induced by the negative portion of the wave. The vibration of a structural element of different natural frequency may, of course, be damped during the pull phase. The nature and amplitude of the free vibratory response obviously



a. Two successive positions (later one dotted) of shock wave before original shock reaches corner 0; 1 indicates original "free-air" shock, and 2 the shock reflected once (p = free-air overpressure; P = ground pressure = 2p).



b. Shock wave after reaching 0; 3 is shock reflected twice, and 4 is shock reflected three times.

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FIGURE E-1 Overpressure Reflection in a 90° (2-Sided) Corner

depend on the relationship between the natural frequency of the element loaded and the duration of the loading pressure wave.

The frequencies of interest in this structural response analysis range from about 2 cps (the natural frequency of the largest standard-size plate glass panels) to 30 cps (the natural frequency of a wall, floor, or ceiling panel). Some elements, principally glass, may have higher frequencies, as for example 150 cps for an 8 x 10 panel of single-strength glass. However, as will be shown below, at these frequencies natural vibration has little effect on stress.

E.3 DYNAMIC STRESS AMPLIFICATION

A dynamic loading like the N-wave induces a different stress than an equivalent static loading. The broken line in Figure E-2 traces the stress amplification factor as a function of the ratio of the N-wave duration to the natural period of the loaded element for zero damping factor. During the

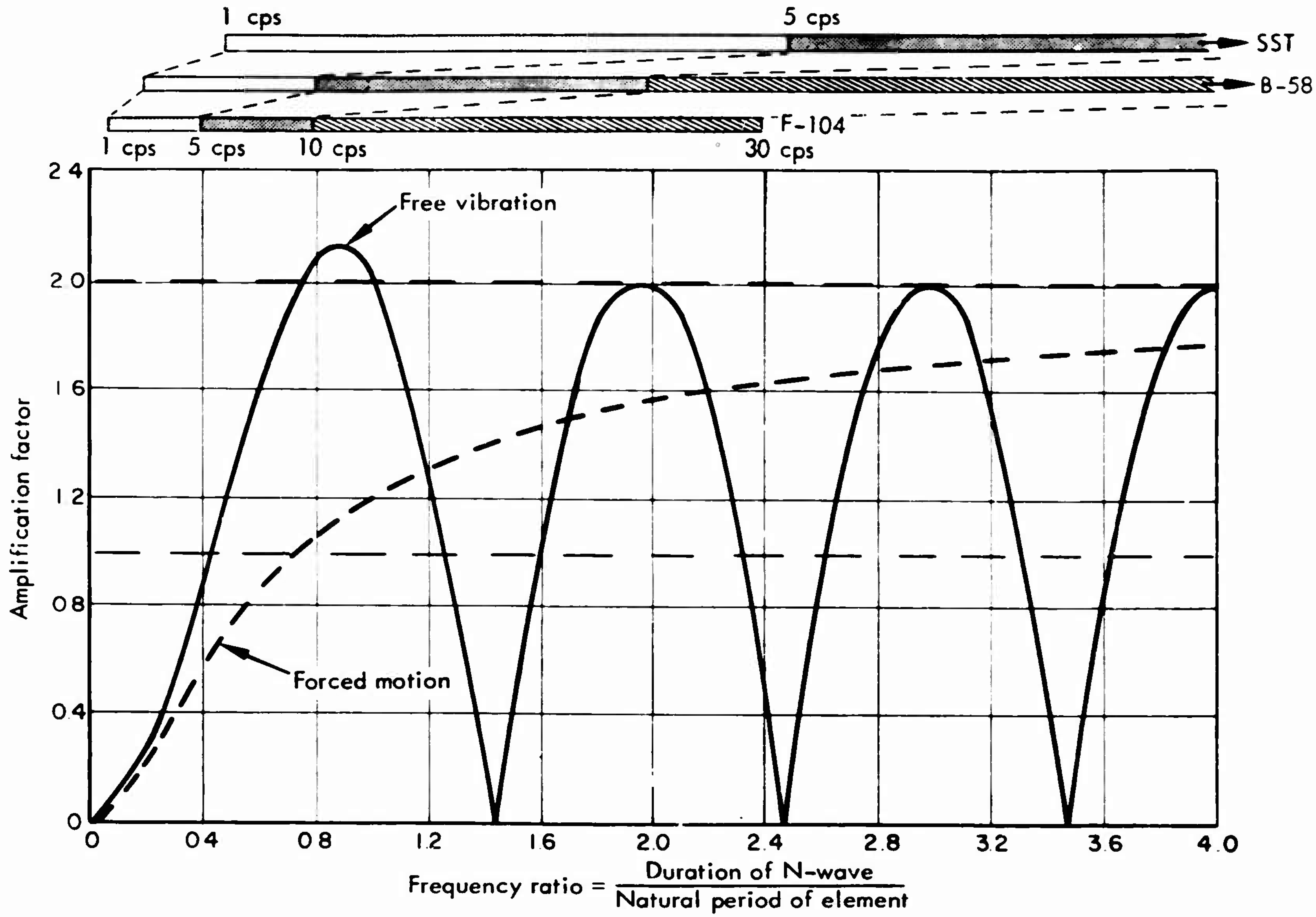

FIGURE E-2 Stress Amplification Factor for a Structural Element Subjected to N-Wave Loading

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[redacted]

forced- motion loading, the amplification factor increases from less than 1.0 for a low frequency ratio to values approaching 2.0 for higher frequency ratios. Where damping exists, the resulting lower amplification factors would be described by characteristic curves for a given damping factor, with the envelope of all such curves defined by the broken line of Figure E-2.

Following the dynamic loading, vibratory motion may set in. For the more usual case of vibration in the fundamental mode, the amplification factor would vary as a function of the frequency ratio according to the solid line in Figure E-2. For a given loading and its corresponding frequency ratio, the curve which indicates the higher ordinate value gives the stress amplification factor. Since forced and free vibrations cannot occur simultaneously, the factors should not be added.

For frequency ratios smaller than about 1.2, free vibration gives the maximum amplification factor, i.e., the stress reaches its peak after the pressure loading is ended. The maximum amplification, which occurs during free vibration at a frequency ratio of about 0.86, is 2.2. For large ratios (as with elements of shorter natural periods) forced motion predominates for most of the frequency ratio range, but in either case amplification factor stays around 2.0. Figure E-2 shows that when the duration of loading is longer than the natural period of the element, the chance increases for the amplification value to fall on the broken line. The case of the small window panes applies.

Larger elements, such as large plate glass panels, will be susceptible to wide variation of stress amplification from sonic booms generated by different aircraft. The natural periods of these panels (2 to 10 cps) are such that the frequency ratios produced with currently operational supersonic aircraft lie between 0.16 and 1.6. In this zone, the excitation of natural vibration also makes possible the peak amplification value of 2.2. The occurrence of applicable frequency ratios with various aircraft is indicated in Table E-1. A comparison of the values in this table to the curves in Figure E-2 indicates that the SST boom will not be critical in the frequency range of plate glass of commonly used sizes (10 to 20 cps). However, for the largest sizes (with frequencies of 2 to 5 cps) the frequency ratios increase

TABLE E-1

FREQUENCY RATIOS FOR TYPICAL N-WAVE LOADINGS ON STRUCTURAL ELEMENTS

N-Wave Duration, Sec	Frequency Ratio With Element Of Natural Period t Sec		
	t = 0.5	t = 0.1	t = 0.33
0.08 (F-104)	0.16	0.8	2.4
0.16 (B-58)	0.32	1.6	4.8
0.5 (SST)	1.0	5.0	15.0

from values with low amplification factors (with the F-104 and B-58) to values with maximum stress amplification (with the SST).

E.4 OVERPRESSURE VS. IMPULSE

There has been some concern that structural responses might be a function of the impulse value rather than the overpressure. The impulse is a measure of the force and duration of the shock wave expressed as lb-sec/ft^2, and is represented by the area under the N-wave pressure trace. For idealized wave forms, the impulse values for two waves at the same overpressure level would be in direct proportion to the duration of the wave, so that the impulse value for an SST sonic wave is about five times that for a fighter at the same overpressure. There would be obvious basis for concern if structural responses were multiplied by this factor. One object of this study was to examine this question.

Theoretical analyses, as reflected in the curves of Figure E-2, suggest that the duration of the loading, i.e., the time component of the impulse value, does determine the value of the stress amplification factor. However, as the preceding discussion indicates, this effect is relatively small for the natural periods of vibration of most structural elements of interest. This is particularly so for the SST, which produces frequency ratios greater than those of smaller aircraft. The evidence produced in the FAA program on the question posed is presented in Section 5 and Appendix D.